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Increase the Allowable Content of Recycled Crushed Concrete Aggregate in Class P Concrete

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16. Abstract

Over 140 million tons of recycled concrete aggregate (RCA) are produced in the United States per year (ACPA, 2009), and this material has been used in a host of transportation infrastructure applications, including fills, embankments, bases, subbases, and concrete pavements. Currently, TxDOT limits the maximum amount of recycled crushed concrete fine aggregate (RCFA) allowed in Class P paving concrete to 20% (by mass replacement of virgin sand). The goal of this project was to evaluate the key technical and construction-related issues that potentially limit the RCFA content in new concrete pavements, and based on laboratory and field evaluations, provide recommendations on maximum RCFA contents. These objectives were accomplished through a thorough review of literature and current practice, conducting a comprehensive laboratory investigation, and constructing and monitoring new pavement sections containing up to 70 percent RCFA. The successful use of recycled concrete aggregate (RCA) in continuously reinforced concrete pavement (CRCP) in a field trial near Sealy, TX under this project demonstrated the potential for increasing the sustainability of concrete paving while still achieving target performance. Based on the findings from this project, it is recommended that TxDOT increase the allowable RCFA content to 70 percent. More work is needed to see if even higher RCFA contents are technically and practically feasible, and more monitored field trials are recommended to evaluate a much more widespread use of RCFAs in implementation project(s).

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Chapter 1. Introduction and Scope

1.1. Introduction and Scope

In a world with diminishing natural resources and an increasing emphasis on sustainability, it is becoming more and more important to recycle and reuse products ranging from water bottles to batteries to construction materials. As the world's most widely used construction material (besides water), portland cement concrete is an ideal candidate for implementing sustainability on a grand scale, especially with regard to recycling and reuse. It has been estimated that over 140 million tons of concrete are recycled each year in the United States (ACPA 2009). This includes concrete recovered and recycled from demolished pavements and structures, as well as concrete returned to ready-mix plants. Obla et al. (2007) reported that about five percent of the 455 million cubic yards of concrete produced annually in the United States is returned to the plant for various reasons, including customers who bought more concrete than was needed and loads that were rejected at the job site (e.g., due to noncompliance with job site requirements, such as slump or air content). Most commonly, recycled concrete is crushed and used as aggregate for fill, road base or new concrete. Typically for new concrete, recycled concrete aggregates are used as an alternative for natural coarse aggregates. There are fewer instances of the use of recycled concrete aggregate as a replacement for natural fine aggregates. Global demand for quality coarse and fine aggregate has resulted in a shortage of these materials, especially sand, in much of the world which has instigated the need to explore other options such as recycled concrete fine aggregate (RCFA).

Developing a better understanding of RCFA and its uses will promote its increased use as an alternative to natural fine aggregate. The use of RCFA has the potential to provide both cost savings and environmental benefits to users through (1) reduced cost for raw materials, (2) energy savings from less processing and transportation (3) reduced disposal of concrete in landfills, (4) conservation of natural resources.

1.2. Organization of Report

This report is presented in the following chapters:

Chapter 2 provides a review of literature and synthesis of current practice and state-of-the-art use of recycled concrete fine aggregate (RCFA).

Chapter 3 provides an overview of the materials including material characterization, laboratory evaluations of fresh and hardened properties and durability of RCFA concrete.

Chapter 4 describes the field trial and the evaluation of RCFA concrete mixtures.

Chapter 5 summarizes the main findings from this research project, including the identification of research needed to increase and improve the use of RCFA in concrete pavements. Guidance is presented, based on current knowledge, on how to evaluate the potential use of RCFA in concrete pavements.

Chapter 2. Literature Review

2.1. Introduction

This literature review is intended to provide background information on RCFA products and material properties. The effects of RCFA on fresh and hardened concrete properties will also be explored. An informal review of the state of current practice regarding the use of RCFA by DOTs throughout the US was also conducted and results are provided.

2.2. RCFA Products and Material Properties

2.2.1. Sources and Production Methods

There are multiple sources of recycled concrete aggregates. As stated earlier, the most common sources for recycled concrete aggregates are construction and demolition waste including demolished pavements and structures.

Concrete pavements have been recycled for over 40 years, with the recycled concrete used in paving applications, bridges (rare in recent years), and geotechnical application such as in bases, subbases, or fills. Concrete pavements are recycled in at least 41 states (see Figure 2.1), including Texas, with the recycled concrete specified and used in various transportation infrastructure applications, including as an aggregate (coarse and/or fine) in new concrete pavement construction.

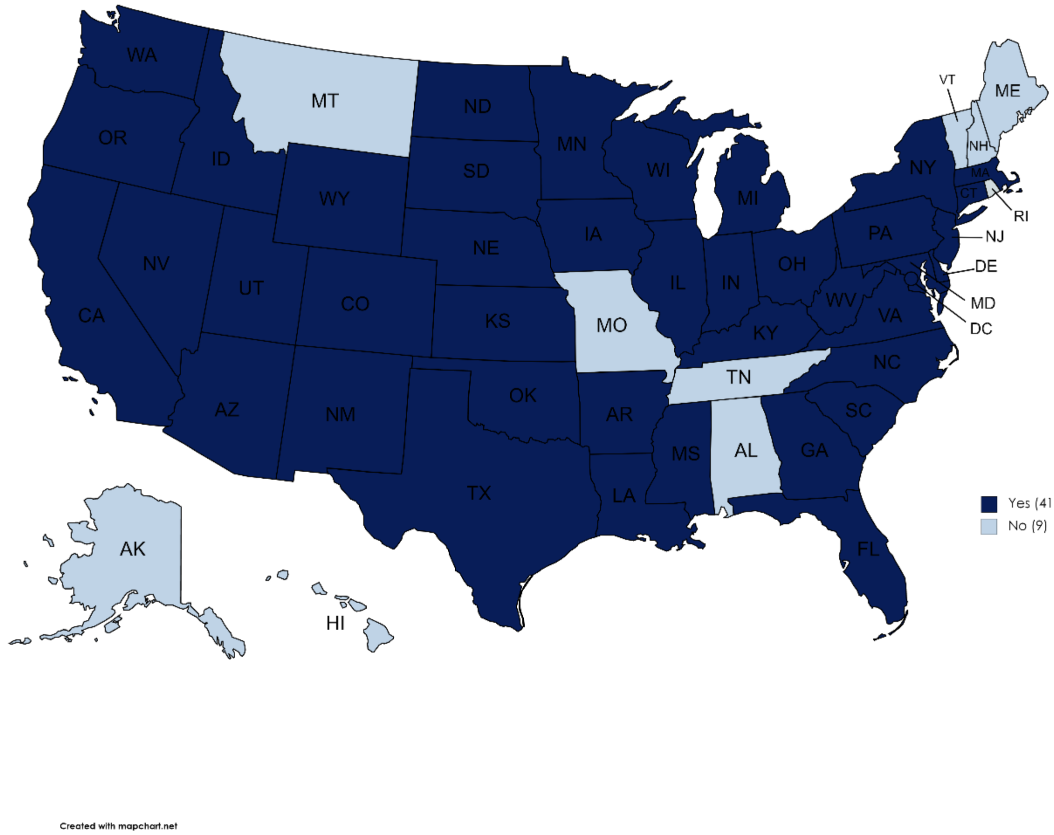

Figure 2.1 – State highway agencies that have used RCA in new concrete pavements (FHWA 2004)

Recycled concrete aggregates are produced through the crushing and sizing of waste concrete and removing of undesired materials, as depicted in Figure 2.2. Examples of undesired materials include steel (rebar, etc.), soil, clay balls, asphalt, and other materials that could adversely impact the performance of RCA. Various types of crushers are used (see Figure 2.3), and crushing is performed in stages (primary crusher, secondary crusher, etc.), with each stage further reducing the size of the crushed concrete.

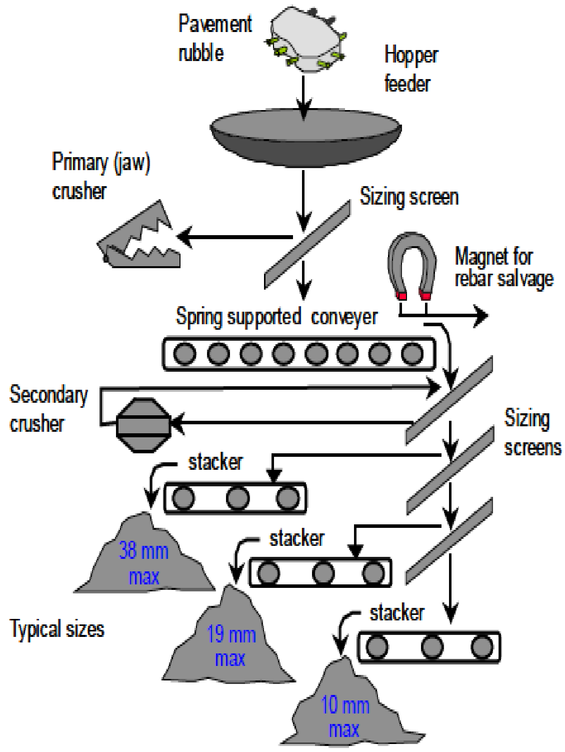

Figure 2.2 – Schematic representation of crushed concrete production facility (Hoerner et al., 2001)

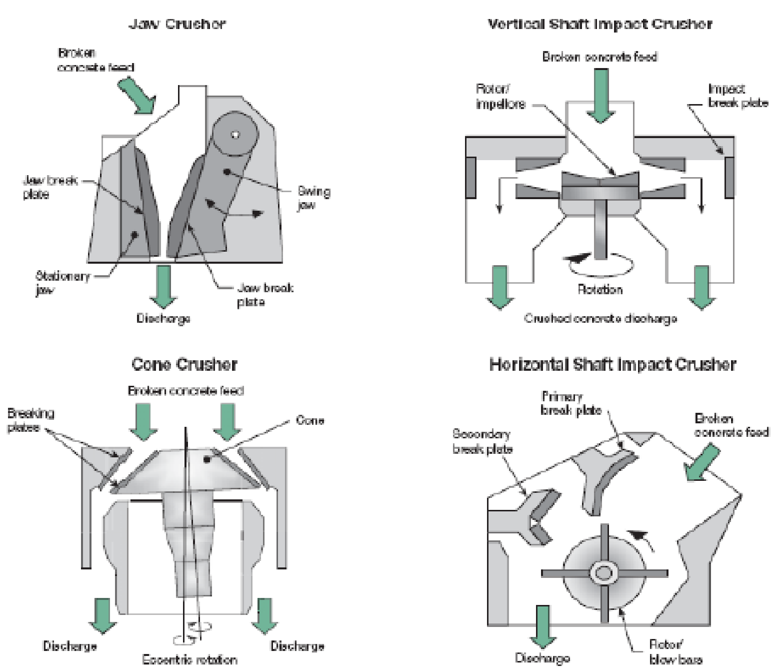

Figure 2.3 – Schematic illustration of different types of concrete crushing equipment (ACPA 2009)

Approximately 190 million tons of concrete debris are created each year, making it the largest component of the solid waste stream (Mcintyre et al, 2009). Of this amount, roughly ¾ of the debris is recycled, processed, and reused as RCA across a range of applications, as previously described.

2.2.2. RCFA Uses

RCFA is currently used, in limited quantities, in low-grade applications such as a substitute material for natural sand in masonry mortars, road constructions and as a filling material for geosynthetic reinforced structures and soil stabilization (Nedeljkovic et al, 2021). Most DOTs have placed restrictions on the use of RCFA in new concrete mixtures due mainly to concerns regarding high absorption capacity and subsequent low workability. For example, TxDOT currently only allows 20% replacement of RCFA in concrete mixtures.

2.3. Effects on Concrete Properties

2.3.1. Laboratory Testing

When considering the use of RCA in concrete pavements, it is important to realize that many of the same factors affecting the performance of natural aggregates in concrete are relevant for both recycled concrete coarse aggregate (RCCA) and recycled concrete fine aggregate (RCFA). As such, it is prudent to first describe how natural aggregates affect concrete pavement performance before discussing some of the important differences between and virgin aggregates and RCA.

Under NCHRP Project 4-20C, Folliard and Smith (2002) identified the aggregate properties that most affect the performance of concrete used in jointed plain concrete pavements (JPCP) and continuously reinforced concrete pavements (CRCP). Table 1 summarizes the aggregate properties that that affect key performance parameters for all pavement types.

Table 2.1: Aggregate properties affecting performance of concrete pavements
(Folliard and Smith 2002)

Aggregate Property	KEY PERFORMANCE PARAMETERS										
	AAR	Blowups	D-Cracking	Longitudinal Cracking	Roughness*	Spalling	Surface Friction**	Transverse Cracking	Corner Breaks	Joint Faulting	Punchouts
Absorption			X								
Abrasion Resistance				X			X	X	X	X	X
Angularity				X			X	X	X	X	X
Coefficient of Thermal Expansion		X		X		X		X	X	X	X
Elastic Modulus		X		X	X	X		X	X	X	X
Gradation				X	X	X		X	X	X	X
Hardness				X			X	X	X		
Mineralogy	X	X	X	X		X	X	X	X		
Porosity and Pore Structure	X		X								
Shape				X			X	X		X	X
Size	X		X	X		X		X		X	X
Strength				X		X		X	X		X
Texture				X		X	X	X	X	X	X

* Because roughness is affected by the presence of distresses, any aggregate properties that influence the development of those distresses will also influence the development of roughness.

** Surface friction is mainly affected by the polish resistance of fine aggregates because of the presence of the mortar-rich layer at the top surface of PCC pavements.

In general, the aggregate properties and recommended test methods shown in Table 2.1 are directly applicable to the use of RCA as partial or full replacements for virgin aggregates. However, there are several issues specific to RCA that may require further evaluation, alternative test methods, or alternative specification limits. Some of the concrete properties that are particularly important when considering RCA in concrete pavements include the following:

- Due to the angular shape, rough surface texture, and relatively high absorption capacity of RCA, the workability and finishability of concrete may adversely be affected, especially at high replacement levels of RCFA (ACPA 2009).

- Bleeding of fresh concrete is reduced when using RCA, especially when using high contents of RCFA. This can adversely affect fresh concrete by increasing the likelihood of plastic shrinkage cracking, especially in hot, windy, and dry conditions.

- Obla et. al, (2007) reported that concrete containing RCA may set up to an hour faster than similar concrete containing virgin aggregates, perhaps due to the accelerating effects of hydrated cement paste within the RCA particles, especially with RCFA.

- Reza and Wilde (2017) stated that the use of RCA typically decreases the compressive and flexural strength of concrete, but that modifications to mixture proportions (e.g., lower w/cm) and the use of chemical admixtures (e.g., water reducers) may help to offset these reductions in strength.

- The potential causes of reduced strength when using RCA include high variability within a given RCA stockpile and higher water demand (due to shape, texture, and absorption effects). Snyder & Cavalline (2016) proposed that RCFA has a more profound effect in reducing concrete strength than RCCA because the latter contains more virgin aggregates and less adhered cement paste.

- The elastic modulus of concrete is typically reduced with increasing RCA replacement levels, for some of the same reasons responsible for reductions in strength. In addition, the stiffness of mortar is less than that of natural aggregates, so increasing RCA contents inherently reduce the stiffness of concrete. For concrete pavements, this can be advantageous as a lower elastic modulus translates to lower stresses for the same strain, which could be induced by loading, drying shrinkage, or temperature changes. This may be particularly relevant for CRCP, where the experience in Texas has shown that high modulus river gravels can result in pavement spalling, especially because such river gravels also exhibit a higher coefficient of thermal expansion.

- Cuttell et al. (1997) reported higher drying shrinkage for concrete containing RCA, compared to similar concrete containing virgin aggregates, owing mainly to the increase in paste content in the RCA. Whether this leads to an increased risk of shrinkage cracking is uncertain, due to parallel reduction in elastic modulus and possible increase in creep imparted by RCA.

- Concrete containing high levels of RCA, especially RCFA, may experience more issues with freezing and thawing and salt scaling, especially if difficulties were had in achieving the target air void system (e.g., target total air content, spacing factor, and specific surface). The higher surface area of RCFA, coupled with higher absorption capacity, can make it more difficult to achieve the desired air void system.

- Concrete that previously suffered from ASR may increase the chance of ASR when that same concrete is crushed and used as RCA in new concrete. If the coarse aggregate in the source concrete was the source of reactivity, it may be difficult to prevent the same aggregate from expanding in new concrete because pore solution alkalinity reductions imparted by SCMs or lower alkali cements may not have the ability to reduce the pH within the mortar layers adhered to the original coarse aggregate particle. In addition, alkalies remaining from the original concrete mixture may be released into the new concrete, increasing the potential risk of ASR. A complicating factor is that RCA, especially RCFA, when exposed to moisture during processing or stockpiling will experience leaching of alkalies, lessening this potential effect. The variability in the exposure history (e.g., availability of moisture) of RCA sources makes this a bit of challenge in estimating the potential impact on new concrete that also contains reactive aggregates.

- Although D-cracking has not been observed in Texas pavements, concrete containing RCCA that was originally made from aggregates susceptible to D-cracking can result in D-cracking in the new concrete, provided that larger aggregate sizes still exist in the RCCA and that the new concrete is exposed to freezing and thawing, high levels of moisture, and especially when the new concrete is subject to frequent applications of deicing salts.

- Concrete that was exposed to significant levels of external chlorides (e.g., marine exposure or exposure to anti-icing or deicing) before being recycled and turned into RCA may increase the likelihood of corrosion of reinforcing steel in CRCP or other reinforced concrete elements. As such, it is critical to measure the potential chloride contribution of RCA to the new concrete using hot water extraction (as opposed to Soxhlet extraction method typically used for virgin aggregates).

Snyder (2018) summarized the typical properties of RCA, compared to natural aggregates, and the relative effects of using RCA (both RCFA and RCCA) on concrete properties in Table 2.2 and Table 2.3, respectively. The actual difference between RCA and natural aggregates properties, as well as the difference between concrete properties, depends on the source, type, and amount of RCA used.

Table 2.2: Typical properties of natural and recycled concrete aggregates (Snyder, 2018)

Material	**Natural aggregates**	**Recycled concrete aggregates**
Absorption capacity	0.8–3.7	3.7–8.7
Specific gravity	2.4–2.9	2.1–2.4
LA Abrasion (% loss)	15–30	20–45
Sodium sulfate soundness (% loss)	7–21	18–59
Magnesium sulfate soundness (% loss)_	4–7	1–9
Chloride content	0–2	1–12

Table 2.3: Relative effects of RCA on concrete properties (Snyder, 2018)

Property	**Range of expected changes in concrete properties when using both RCCA and RCFA, compared to similar mixtures containing virgin aggregates**
Water demand	Much greater
Finishability	More difficult

Air content (including air in the original paste)	Higher
Setting time	Increased
Bleeding	Less
Compressive strength	15–40% lower
Tensile strength	10–20% lower
Elastic modulus	25–40% lower
Drying shrinkage	70–40% higher
Thermal expansion	0-30% higher

In addition to the potential impact on concrete properties, there are some issues related to handling of RCA, including stockpiling. Some of these issues include:

- When RCA stockpiles are exposed to moisture (precipitation), alkalies and lime will leach from the piles, creating an alkaline runoff, which may represent an environmental concern in some cases. The release of alkalies from the stockpile may be fairly rapid, especially for RCFA (owing to its high surface area).

- RCA, especially RCFA, will react with the environmental CO_2 to form calcium carbonate, which can reduce the potential for leaching of calcium. There may be some minor effects on hydration due to the presence of calcium carbonate, when in finely divided form can lead to the formation of carboaluminate hydrates. It is also possible that the calcium carbonate may act as a nucleation site for C-S-H formation, as has been observed in portland limestone cement systems, although this has not been reported in literature.

- RCA is partially composed of unhydrated cement compounds, which can hydrate upon exposure to water. This is mainly an issue for RCFA, due to the higher surface area, and as such, RCFA stockpiles may need to be protected from direct moisture while being stockpiled (ACPA 2009)

2.3.2. Field Trials

There have been few instances in which RCFA has been used in large-scale field trials. However, one of the most ambitious and successful projects to utilize RCA in pavement construction was conducted by TxDOT (M. C. Won 2001). In 1995, TxDOT began reconstruction of a section of continuously reinforced concrete pavement on IH-10 in Houston. For this project, recycled concrete was used for both coarse and fine aggregates. Demolished concrete from the existing concrete pavement was used as the source for both RCA and RCFA. The objectives of this study were to evaluate (1) the material properties of recycled concrete aggregate, (2) their effect on paving operations, and (3) in-situ concrete properties to identify the reasons for good pavement performance. The scope of this study included (1) laboratory evaluation of recycled concrete aggregate, (2) field evaluation of paving operations, and (3) evaluation of the field performance of CRCP sections containing 100 % RCA.

Laboratory results in this study were consistent with observations of others as previously discussed. Observations during concrete mixing and paving operations indicated that moisture control of recycled aggregate, especially fine aggregate, is critical in producing consistent and workable concrete mixes. Additionally, no significant adjustment is needed in paving operations due to the use of 100% recycled coarse and fine aggregate in concrete. Evaluation of field performance of this pavement indicated that pavements constructed with 100% recycled coarse and fine aggregates performs as well or better than pavements constructed with virgin aggregates. In this case, no distress, including spalling, wide cracks, or punchouts took place during the evaluation period. Spalling was the main mode of deterioration and reason for reconstruction of the previous existing pavement. Additionally, low modulus of concrete and good bond between recycled coarse aggregate and new mortar appears to be the key ingredients of good pavement performance.

2.4. State Highway Department Current Practices

As part of this literature review, the Research Team collected and synthesized information from state highway agencies regarding the use of recycled concrete aggregates in concrete pavements. Table 4 summarizes this information for all 50 states, based on most recent information provided online by each highway agency. Although this table does not include information on actual RCA usage in concrete pavements, it does provide a broad overview of state highway specifications and test methods related to such usage.

Table 2.4: Summary of state highway agencies allowance, test methods, and specifications for recycled concrete aggregates used in concrete pavements

State	**Is recycled concrete aggregate allowed in pavements?**	**Is there a maximum allowable amount of RCA for pavements? If so, what is the limit?**	**What test methods must be performed for RCA for use in pavements?**
Alabama	Yes (for bases)	None specified	AASHTO T 85 (Specific Gravity); AASHTO T 11 (Deleterious Substances); AASHTO T 96 (Abrasion); AASHTO T 104 (Soundness)
Alaska	No	N/A	N/A
Arizona	No	N/A	N/A
Arkansas	No	N/A	N/A
California	Yes	None specified	California Test 213 (Organic Impurities); California Test 217 (Sand Equivalent); California Test 549 (Relative Strength/Shrinkage); California Test 214 (Soundness); California Test 229 (Durability Index)

Colorado	Yes	None specified	AASHTO M 147 (Quality Requirements); AASHTO T 96 (Abrasion); ASTM C535; AASHTO T 89/90 (LL and PI)
Connecticut	Yes	None specified	ASTM D4791; AASHTO T 260
Delaware	No	N/A	N/A
Florida	Yes (coarse only)	None specified	AASHTO T21/71 (Organic Impurities); FM 1-T096 (Abrasion); AASHTO T 104 (Soundness)
Georgia	No	N/A	N/A
Hawaii	No	N/A	N/A
Idaho	No	N/A	N/A
Illinois	Yes	None specified	ITP 104 (Soundness); ITP 11 (Gradation); ITP 21 (Organic Impurities); ASTM C 1260 (Alkali-Aggregate Reaction)
Indiana	No	N/A	N/A
Iowa	Yes	30 percent	ASTM D698
Kansas	No	N/A	N/A
Kentucky	No	N/A	N/A
Louisiana	No	N/A	N/A
Maine	No	N/A	N/A
Maryland	Yes	None specified	EPA Toxicity Leaching procedure; pH; Compaction and moisture content
Massachusetts	No	N/A	N/A
Michigan	Yes	None specified	Freeze-thaw resistance
Minnesota	Yes	40 percent	ASTM C33
Mississippi	Yes	None specified	AASHTO T 96 (Abrasion); AASHTO T 19 (Dry Rodded Unit Weight); AASHTO T 90 (Plasticity); AASHTO T 104 (Soundness); AASHTO T 11 (Gradation)
Missouri	Yes (for bases/sub-bases)	None specified	AASHTO T 96 (Abrasion); AASHTO T 85 (Absorption); MoDOT Test Method TM 14 (Soundness)
Montana	No	N/A	N/A
Nebraska	No	N/A	N/A
Nevada	Yes	None specified	Nev. T206 (Sieve analysis); Nev. T200 (Sampling Aggregate); Nev. T227 (Sand Equivalent); AASHTO T 112 (Clay Lumps); AASHTO T 104 (Soundness); AASHTO T 113 (Lightweight Pieces); AASHTO T 21 (Organic Impurities); AASHTO T 27/11 (Fineness Modulus)
New Hampshire	Yes	None specified	AASHTO M319
New Jersey			
New Mexico	No	N/A	N/A
New York			NYSDOT 207 (Sulfates); NYSDOT 202; AASHTO T 21 (Organic Impurities}; AASHTO T 96 (Abrasion)
North Carolina	Yes (for bases/sub-bases)	None specified	ASTM D5821 (Fractured Faces)\; ASTM D4791 (Flat/Elongated Pieces); AASHTO T 104 (Soundness); AASHTO T 96 (Abrasion); AASHTO T 112 (Deleterious Materials); AASHTO T 327 (Durability)
North Dakota	No	N/A	N/A
Ohio	Yes	None specified	Must meet quality requirements from 703.02B from general specifications manual.
Oklahoma	Yes	None specified	AASHTO T 96 (Abrasion); AASHTO T 210 (Aggregate Durability Index); AASHTO T 176 (Sand Equivalent); OHD L-18 (Fractured Faces); AASHTO T 27 (Gradation)
Oregon	Yes (for bases/sub-bases)	None specified	AASHTO T 113/11 (Harmful Substances); AASHTO T 104 (Soundness); AASHTO T 96 (Abrasion); ODOT TM 208 (Gradation); AASHTO T 335 (Fracture); ODOT TM 229 (Elongated Pieces)
Pennsylvania	Yes	None specified	ASTM C40; ASTM 295; ASTM C142; ASTM D2419
Rhode Island	No	N/A	N/A
South Carolina	Yes	None specified	AASHTO T 21 (Organic Impurities); AASHTO T 104 (Soundness); AASHTO T 96 (Abrasion)
South Dakota	No	N/A	N/A

Tennessee	Yes (for base sub-base, or shoulder coarse)	None specified	AASHTO M 6 (Quality Requirements); AASHTO T 267 (Organic Impurities); AASHTO M 80 (Quality Requirements)
Texas	Yes	20 percent (fine)	ASTM C33; ASTM C 837; ASTM C 39; ASTM D 1633; ASTM C 469; ASTM C 157
Utah	No	N/A	N/A
Vermont	Yes	25 percent	AASHTO T27; AASHTO T 11
Virginia	Yes	None specified	AASHTO T27 (Gradation); AASHTO T 103/104 (Soundness); AASHTO T 21 (Organic Impurities)
Washington	Yes	None specified	AASHTO T 303 (Expansion); AASHTO M 6 (Quality Requirements); AASHTO T 21 (Organic Impurities); AASHTO M 80 (Quality Requirements); ASTM C 33 (Gradation)
West Virginia	No	N/A	N/A
Wisconsin	No	N/A	N/A
Wyoming	Yes (for bases only)	60 percent (in base)	N/A

2.5. Future Research Needs

2.5.1. Standardized Test Methods

One of the main hurdles to widespread use of RCFA is the lack of a standardized method for assessing the absorption capacity and specific gravity of RCFA sources. Absorption capacity and specific gravity are key parameters for designing quality concrete mixture designs. RCFA sources tend to have a significantly higher absorption capacities compared to natural aggregates. Unfortunately, there is no single accepted method for determining these values for RCFA.

Nedeljkovic et al (Nedeljkovic, et al. 2021) synthesized results from 38 different studies investigating absorption capacity of RCFA. The reported absorption capacity values for RCFA varied between 4.3 and 13.1% with an average of 8.4%. The scatter with respect to absorption capacity and specific gravity values between different studies is caused by variations in the quality of parent concrete, which is often unknown (water-to-cement ratio, type and amount of cement, aggregates origin and gradation, etc.), and is to be expected; however, reported values are also strongly influenced by the procedure, size fraction of RCFA, specimen weight and agglomeration of small particles. These differences between actual and reported values for absorption capacity and specific gravity can greatly affect mixture design and ultimately workability in the field. Development of a standard test method for evaluating absorption capacity of RCFA is needed in order to make RCFA a viable substitute for natural fine aggregates.

2.5.2. Additional RCFA Field Trials

High absorption capacity and lack of moisture control of recycled aggregates are the primary reasons for inconsistent workability in concrete mixtures with RCFA. Practitioners need more experience using recycled fine aggregates in order for the material to gain traction in the concrete industry. Many studies have been published on the use and positive performance of recycled concrete used for coarse aggregates, but much of the literature on recycled concrete fine aggregates tends to focus solely on the negative impacts of RCFA on concrete mixtures. Implementation of more large-scale field trials that incorporate the use of RCFA for concrete pavement construction will help remove any inaccurate assumptions associated with the use of RCFA.

Information obtained from additional RCFA field trials will not only improve best practices for concrete mixing and paving operations, but would also provide valuable insight into the long-term performance of RCFA concrete pavements.

Chapter 3. Laboratory Evaluation of RCFA

This chapter presents the findings of a comprehensive laboratory investigation on the use of RCFA in concrete. Each of the recycled concrete fine aggregates was evaluated separately and then used in combinations of other materials to produce concrete meeting Class P concrete requirements.

3.1. Overview of Materials

The list of the materials selected and procured for this project is shown in Table 3.1. After a comprehensive search for commercially available RCFA, three sources were procured, all from the Houston area. Two sources were fine aggregates; the third source was a recycled coarse aggregate which was blended with one of the recycled fine aggregate sources to obtain optimal grading.

Table 3.1: Materials being evaluated in the laboratory testing program

Material	# of sources	Designation	Information on sources/types of materials
Portland Cement	3 sources	CM1	ASTM C150 Type I /II
		CM2	ASTM C150 Type I /II (Contractor)
		CM3	ASTM C595 Type IL (Contractor)
Fly Ash	1 source	FAF	Class F Fly Ash
	1 source	FAC	Class C Fly Ash
Coarse Aggregate	2 sources	CA1	Grade 2 Limestone – Lab
		CA2	Grade 2 Limestone - Contractor
Fine Aggregate	4 sources	FA	ASTM C33 Siliceous Sand - Lab
		FA2	ASTM C33 Siliceous Sand - Contractor
		FA3	Reactive siliceous sand (ASR Testing)
		FA4	Graded Ottawa sand (Sulfate testing)
Recycled Concrete Aggregate	3 sources	RCFA1	Recycled Fine Aggregate (Holmes)
		RCFA2	Recycled Fine Aggregate (Crawford)
		RCCA	Recycled Coarse Aggregate (Webber)
High-range water reducer	1 source	HRWR1	Polycarboxylate

3.2. Characterization of Raw Materials

3.2.1. Cement and Fly Ash

All cements and fly ashes used in this research are commercially available products. Each material was analyzed with x-ray fluorescence (XRF) to determine the bulk oxide contents. Table 3.2 provides the chemical composition of the cements and fly ash. CM1 and CM2 are ASTM C 150 I/II cements and CM3 is an ASTM C595 Type IL cement with 12% limestone.

Table 3.2: Chemical Composition of Cementitious Materials (% by mass)

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	K_2O	Na_2O	LOI
CM1	20.6	5.0	3.4	64.8	2.8	1.1			3.0
CM2 - Webber	20.3	4.6	3.7	64.7	2.8	1.2	0.52	0.15	2.5
CM3 - Webber					2.8		.49	.13	6.2
Class F Fly Ash	53.0	21.69	5.00	12.26	0.53	2.58	0.98	0.15	0.25
Class C Fly Ash	36.98	19.42	5.52	24.90	1.42	5.06	0.59	1.92	0.20

3.2.2. Recycled Concrete Fine Aggregates

For each of the recycled concrete fine aggregates procured for this project, a comprehensive evaluation of the source is being performed, including the following:

- Gradation (including fineness modulus) (ASTM C33)
- Specific gravity and absorption (ASTM C 128)
- Clay lumps and organic impurities (ASTM C142)
- Sand equivalent (ASTM D2419)
- Smectite clay via Methylene Blue test (ASTM C1777)
- Chloride content (ASTM C1218)
- Water-soluble alkali content (hot water extraction, after Berube et al. 2002)
- Acid insoluble test (Tex-612-J)
- Micro-Deval test (ASTM D 7428)

These are common test methods for fine aggregates and may not be suitable for recycled concrete fine aggregates.

3.2.2.1. Specific Gravity and Absorption and Gradation

Table 3.3 provides the specific gravity and absorption for the two RCFAs used in this project. Compared to standard fine aggregates, RCFAs exhibit a lower specific gravity and higher absorption capacity, owing to the porous nature of crushed concrete. The two RCFAs had surprisingly similar gradations, which may be due to the use of similar crushing equipment used at the two facilities. However, neither of the RCFAs met the standard requirements concrete fine aggregates, as per ASTM C33. Table 3.4 shows in red the sieves that do not conform to the prescribed gradations set for by ASTM C33. It should be noted that these recycled fines were commercially available to be concrete sands and they are sold as minus 3/8's material. Table 3.5 shows the recycled coarse aggregate gradation. Similar to the fine aggregate, this recycled coarse was procured knowing that it did not fit any coarse aggregate gradations for concrete. It was procured from the onsite contractor for the Sealy project discussed in Chapter 4 who was using the crushed rock for base material.

Table 3.3: Specific gravity and absorption measured for RCFA1, RCFA2 and RCCA1

Recycled Concrete Fine and Coarse Aggregate Sources	Specific Gravity	Absorption Capacity (%)
Cherry – Houston, TX. Crawford (RCFA1)	2.10	7.5
Cherry – Houston, TX. Holmes (RCFA2)	1.99	10.3
Webber (RCCA1) - Sealy, TX	2.31	7.7

Table 3.4: Fine Aggregate Gradation for RCFA1 and RCFA2

Seive Size	RCFA-1 (Holmes)	RCFA-2 (Crawford)	C33 Grading FA Requirements	
	Percent Passing (%)	Percent Passing (%)	Min Percent Passing (%)	Max Percent Passing (%)
3/8"	96	96	100	
NO. 4	78	74	95	100
NO. 8	59	58	80	100
NO. 16	44	45	50	85
NO. 30	31	33	25	60
NO. 50	18	19	5	30
NO. 100	7	7	0	10
NO. 200	2	2	0	3

Table 3.5: Coarse Aggregate Gradation for RCCA1

Seive Size	RCCA-1	C33 Grading CA Requirements	
	Percent Passing (%)	Min Percent Passing (%)	Max Percent Passing (%)
2 in	100	90	100
1.5-in	95	0	15
3/4-in	79	0	5
3/8-in	64	--	--
No. 4	48	--	--

3.2.2.2. Clay Lumps and Organic Impurities

Excessive clay lumps in a processed aggregate intended for use in a concrete mixture may interfere with the bonding between the aggregate and cementitious material. This can result in spalling if the material is incorporated into the pavement or structure. ASTM C142 was followed to determine the amount of clay lumps and friable particles within the RCFA sources. This method of test covers the procedure for the determination of clay lumps and friable particles in either fine or coarse aggregates. Clay lumps and friable particles are objectionable materials in the aggregate due to contamination at the time the deposit was formed, at the time of quarrying, or at the time of hauling and handling. Clay lumps and friable particles are considered any agglomerated or soft particles retained on the #4 sieve and greater, and will include such terms as mud and clay balls.

The TxDOT specification for Class P pavements limits the weight of clay lumps present within a fine aggregate source at 0.5% maximum. The percentage of clay lumps present within RCFA1 and RCFA2 were 14.9% and 16.5%, respectively, which is in great excess of the TxDOT maximum allowable amount.

3.2.2.3. Sand Equivalent

The sand equivalent test is used to determine the relative proportion of detrimental fine dust of clay-like particles in soils or fine aggregates. ASTM D2419 was used to evaluate the sand equivalent value for both RCFA sources. The sand equivalent values for RCFA1 and RCFA2 were 25 and 26.2, respectively. TxDOT Item 421: Hydraulic Cement Concrete allows a maximum sand equivalent value of 80 per TxDOT test procedure Tex-203-F. Both RCFA sources comply with the TxDOT sand equivalent requirements.

3.2.2.4. Smectite Clay via Methylene Blue Test

ASTM C1777 is used to determine the amount of methylene blue absorbed by a specimen of fine aggregate or mineral filler. The result is reported as a methylene blue value in units of mg of methylene blue adsorbed per gram of fine aggregate or mineral filler. The methylene blue value is a function of the amount and characteristics of clay minerals present in the test specimen. High values indicate increased potential for diminished fine aggregate performance in a concrete mixture. All three recycled concrete aggregate sources were evaluated with ASTM C1777 and the results were 7.66mg/g (RCFA1), 7.51mg/g(RCFA2), and 7.49mg/g (RCCA1). The fine aggregate requirements established by TxDOT in TxDOT Item 421: Hydraulic Cement Concrete allow a maximum of 0.50% weight of clay lumps per TxDOT test procedure Tex-413-A. These results indicate that the recycled materials contain a very high clay content which could lead to a reduction in durability if utilized in concrete mixtures.

3.2.2.5. Water Soluble Alkali Content

The water soluble alkali test (Berube 2002), also known as the hot-water extraction method, was used to determine the alkali loading of the RCFA sources. This test method is typically used to determine the current alkali loading in concrete structures through the use of concrete core samples that are then crushed and tested. RCFA is sourced by crushing demolished concrete structures, typically of unknown or hard to trace origins, making it important to determine the alkali loading of each source prior to use.

The average alkali loading for RCFA1 and RCFA2 was 1.96 and 1.94 kg/m^3 Na_2O_{eq} (3.31 and 3.27 lb/yd^3 Na_2O_{eq}), respectively. It is generally accepted that keeping the total alkali content below 3.0 kg/m^3 is an effective method of limiting expansion; however, field structures have exhibited damage with even lower alkali loadings, especially when alkalies have also been contributed by the aggregates in the mixture or by external sources, such as deicing salts (FHWA 2003). The results of the water-soluble alkali tests for the two RCFA sources were below the accepted limit for total alkali loading. However, the overall alkali loading from concrete will be higher when cement is added to the system. Nevertheless, it remains unknown if the alkali-loading of a recycled concrete aggregate will contribute to the total alkali loading of the concrete itself. Data from accelerated laboratory testing such as ASTM C1260 and MCPT as well as large scale exposure site data is needed to provide context for the water-soluble alkali data.

3.2.2.6. Acid Insoluble Test

The acid insoluble test determines the resistance of aggregates to loss when exposed to a hydrochloric acid solution. Tex-612-J: Test Procedure for Acid Insoluble Residue for Fine Aggregate was used to evaluate each RCFA source. The acid insoluble residue for RCFA1(Holmes) and RCFA2 (Crawford) were 58.9% and 65.2%, respectively. For concrete subjected to traffic the acid insoluble content of aggregates shall not be less than 60%. This value correlates to abrasion and skid resistance of the concrete in-situ. These results indicate that concrete produced with RCFA1 (Holmes) would have a slightly reduced abrasion and skid resistance compared to other approved mixtures.

3.2.2.7. Micro-Deval Test

The resistance of fine aggregates to abrasion is evaluated by ASTM D7428. This test method is often referred to as the Micro-Deval Test. The Micro-Deval Test is a measure of abrasion resistance and durability of mineral aggregates resulting from a combination of actions including abrasion and grinding with steel balls in the presence of water. A 500-g sample with standard grading is initially soaked in water for not less than one hour. The sample is then placed in a jar mill with 0.75 L of water and an abrasive charge consisting of 1250 g of 9.5-mm diameter steel balls. The jar, aggregate, water, and charge are revolved at 100 rpm for 15 minutes. The sample is then washed and oven dried. The loss is the amount of material passing the 75 µm sieve expressed as a percent by mass of the original sample. (ASTM International 2015)

The results of the Micro-Deval Test are presented as percent loss of total aggregate. The results for the RCFA sources were:

Percent Loss in Micro-Deval Test

RCFA1 – 26.5%

RCFA2 – 21.1%

The value typically regarded as the upper limit for acceptable performance in the micro-deval test is 17% (Clement 2013). The percent loss for both RCFA sources exceeded this upper limit indicating concrete produced with these aggregates would be expected to have a slight reduction in durability.

3.2.2.8. RCFA Characterization Summary

The recycled concrete fine aggregates did not pass many of the traditional test methods that are suitable for normal concrete sand. Results were similar for both sources of RCFA.

3.2.3. Traditional Fine and Coarse Aggregates

Traditional fine and coarse aggregates from natural sources were also utilized in this study. Coarse Aggregate 1 (CA1) is a limestone aggregate produced by Vulcan Materials in Hondo, TX and Fine Aggregate 1 (FA1) is a river sand produced by Alleyton in Garwood, TX. General properties for these aggregates are listed in Tables 3.6 through 3.8. Both fine and coarse aggregates met the grading requirements.

Table 3.6: Material properties for traditional aggregate sources

Traditional Fine and Coarse Aggregate Sources	Specific Gravity	Absorption Capacity (%)	Unit Weight (SSD)	Fineness Modulus (FM)
Vulcan – Hondo, TX. Medina Quarry (CA1)	2.61	1.5	92.4	N/A
Alleyton – Garwood, TX. Smith Quarry (FA1)	2.63	0.4	N/A	2.69

Table 3.7: Gradation data for traditional coarse aggregate, CA-1.

Seive Size	CA-1- Coarse
	Percent Passing (%)
2.5-in	100
2 in	100
1.5-in	100
1 in	89.8
3/4-in	69.2
1/2-in	39.6
3/8-in	24.7
No. 4	9

Table 3.8: Gradation data for traditional fine aggregate, FA-1

Seive Size	FA-1	C33 Grading FA Requirements	
	Percent Passing (%)	Min Percent Passing (%)	Max Percent Passing (%)
3/8"	100	100	
NO. 4	98.2	95	100
NO. 8	89.9	80	100
NO. 16	74.8	50	85
NO. 30	51.6	25	60
NO. 50	15.9	5	30
NO. 100	1.1	0	10
NO. 200	0.11	0	3

3.3. Mixture Proportions

Table 3.9 shows the original concrete mixtures proposed for testing for this project. This matrix was changed slightly, due to the inability to procure a third RCFA (RCFA3). It was difficult to find commercially available sources of RCFA and most applications are for RCCA in fill or flex base applications.

Table 3.9: Original Proposed RCFA Mixture Matrix

Mixture	Cementitious Materials	Recycled crushed concrete fine aggregate source and content (% replacement of virgin sand)*					
		0%	20%	30%	40%	70%	100%
PC-Control	Type I		RCFA1 RCFA2 RCFA3	RCFA1 RCFA2 RCFA3	RCFA1 RCFA2 RCFA3	RCFA1	RCFA1 RCFA2 RCFA3
PC-F Ash	Type I with 20% Class F Ash		RCFA1 RCFA2 RCFA3	RCFA1	RCFA1 RCFA2 RCFA3	RCFA1	RCFA1

PC-C Ash	Type I with 35% Class F Ash		RCFA1 RCFA2 RCFA3	RCFA1	RCFA1 RCFA2 RCFA3	RCFA1	RCFA1

*RCFA3 was not procured due to inability to find additional source of recycled concrete fine aggregate. RCFA was replaced with a recycled concrete coarse aggregate as shown in Table 3.11.

Results from initial testing efforts indicated minimal differences in mixtures produced with 0-50% RCFA which led to the removal of 30% and 40% RCFA mixtures from the testing matrix. Additionally, a third RCFA source was unavailable so it was also removed from the testing matrix. Table 3.10 shows the final concrete mixture matrix for the project and mixture proportions for each of the mixtures in the testing matrix are listed in Table 3.11.

Initial trial mixtures did not use an optimized gradation which decreased strengths which did not meet the required strengths at 7 and 28 days. The aggregates were optimized using a tarantula curve in which the aggregates were graded to fit the requirements of this curve.

Table 3.10: Final RCFA Mixture Matrix

Mixture	Cementitious Materials	Recycled crushed concrete fine aggregate source and content (% replacement of virgin sand)				
		0%	20%	50%	70%	100%
PC-Control	Type I/II	RCFA1		RCFA1	RCFA1	
PC-F Ash	Type I with 20% Class F Ash	RCFA1 RCFA2	RCFA1	RCFA1 RCFA2	RCFA1 RCFA2	RCFA1 RCFA2
PC-C Ash	Type I with 35% Class F Ash	RCFA1		RCFA1	RCFA1	

*Table 3.11: Mixture proportions for Mixture Matrix**

Mixture	Coarse Aggregate (lb/yd3)	Fine Aggregate (lb/yd3)	Recycled Coarse Aggregate (lb/yd3)	Recycled Fine Aggregate (lb/yd3)	Cement (lb/yd3)	Fly Ash (lb/yd3)	Water (lb/yd3)
RCFA-0	1847	1502	-	-	369	92	234
RCFA-20	1791	1088	-	217	416	104	234
RCFA-50	1728	712	-	568	416	104	234
RCFA-70	1697	437	-	813	416	104	234
RCFA-100	1414	-	-	1389	416	104	234
RCCA-100	-	1265	1667	-	416	104	234
RCCA-100 / RCFA-70	-	380	1667	707	416	104	234
RCCA-70 / RCFA-70	566	380	1167	707	416	104	234

*RCCA was added to the final round of testing as it was procured from the contractor for the field trial (Chapter 4)

3.4. Fresh Properties of RCFA Concrete

3.4.1. Slump

One issue that was expected and has been confirmed is that the incorporation of high replacement levels of RCFA for virgin sand greatly reduces the workability of fresh concrete, as shown in Figure 3.1. Although some of this loss in workability can be offset with a high-range water reducer (HRWR), Figure 1 illustrates the practical challenge associated with higher RCFA replacement levels. A HRWR was used for all laboratory mixtures to achieve a slump between 2-4 inches.

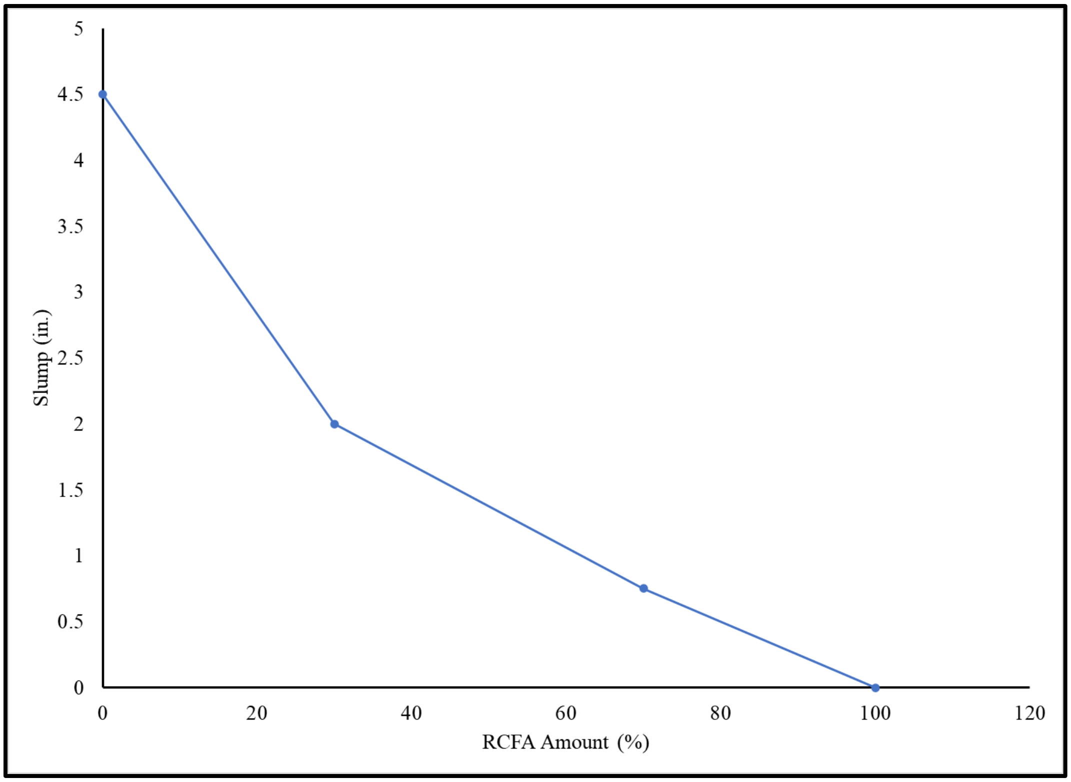

Figure 3.1: Slump Loss with increasing RCFA2

3.4.2. Unit Weight, Air Content, Setting Time, Finishability and Temperature

Additional fresh properties including: unit weight, air content, setting time, amount of bleed water, and temperature were recorded.

There were minimal changes in setting time for concrete mixtures produced with RCFA at any replacement level as shown in Figure 3.2. Overall, both initial and final set times were slightly reduced as the recycled concrete fine aggregate increased.

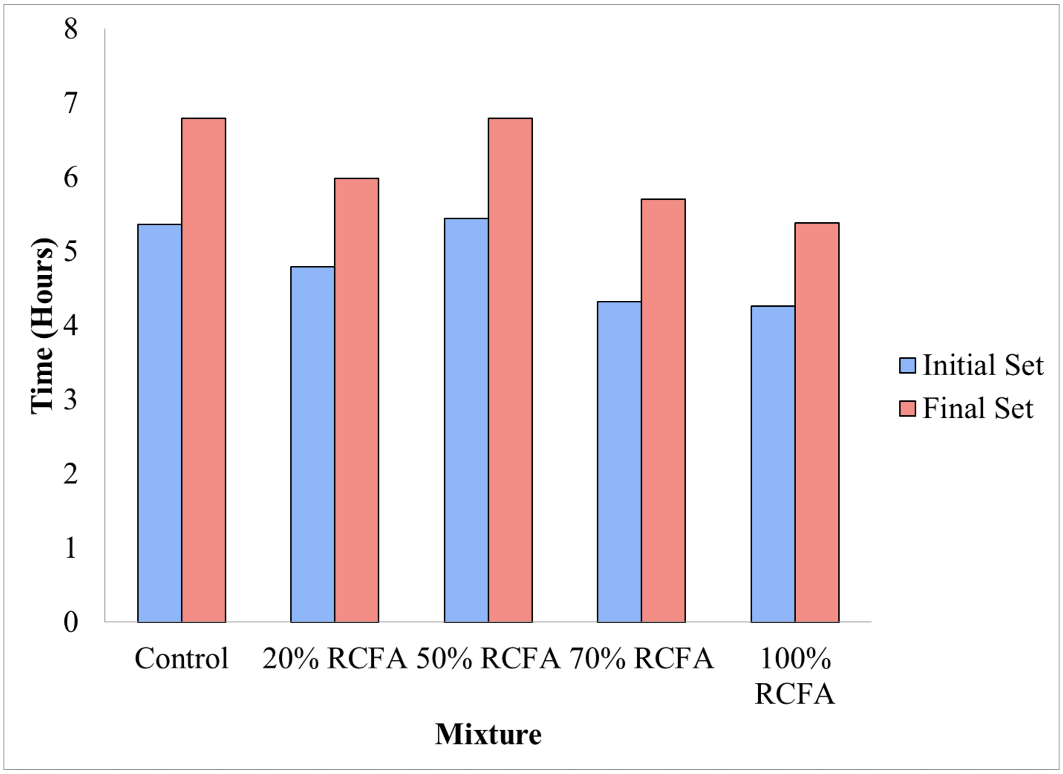

Figure 3.2: Set time of RCFA concrete mixtures.

ASTM C232 was used to evaluate the amount of bleed water produced for each RCFA mixture. Little to no bleed water was produced for mixtures containing 50% RCFA and higher replacements as shown in Figure 3.3. The lack of bleed water can lead to issues with achieving proper finishing requirements and shrinkage of a pavement.

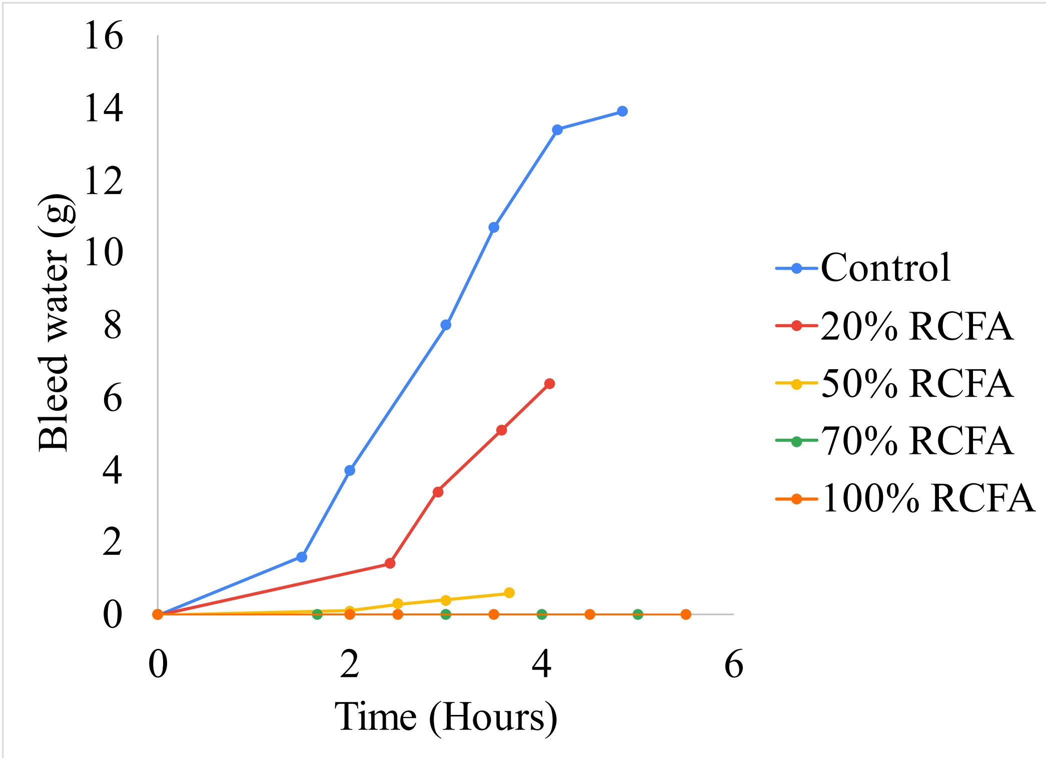

Figure 3.3: Bleed water produced for RCFA mixtures.

Table 3.12 provides the fresh concrete properties for 20% Class F Fly as mixtures containing recycled concrete fine aggregate replacements. The unit weight of the mixtures decreased with increased amounts of RCFA. The mixtures were not air-entrained so the air content was not affected.

Table 3.12: Fresh Concrete Properties

Mixture	Unit Weight (lb)	Air Content (%)	Temperature (F)
Control	146.2	2.1	73.4
20% RCFA	145.9	2	73
50% RCFA	145.5	2.1	73.6
70% RCFA	145	2	72.8
100% RCFA	144	2.8	72.9

3.5. Hardened Properties of RCFA Concrete

3.5.1. Compressive Strength

The compressive strength of all RCFA mixtures was evaluated. Figure 3.4 shows the compression testing results for RCFA mixtures containing 0-70% RCFA in a straight portland cement concrete mixture. At seven days, neither the 50% nor the 70% RCFA mixture reach the benchmark strength of 3,200 psi; however, by 28 days all three mixtures surpass the benchmark strength of 4,000 psi with the 50% RCFA mixture surpassing the compressive strengths of the control mixture with 0% RCFA.

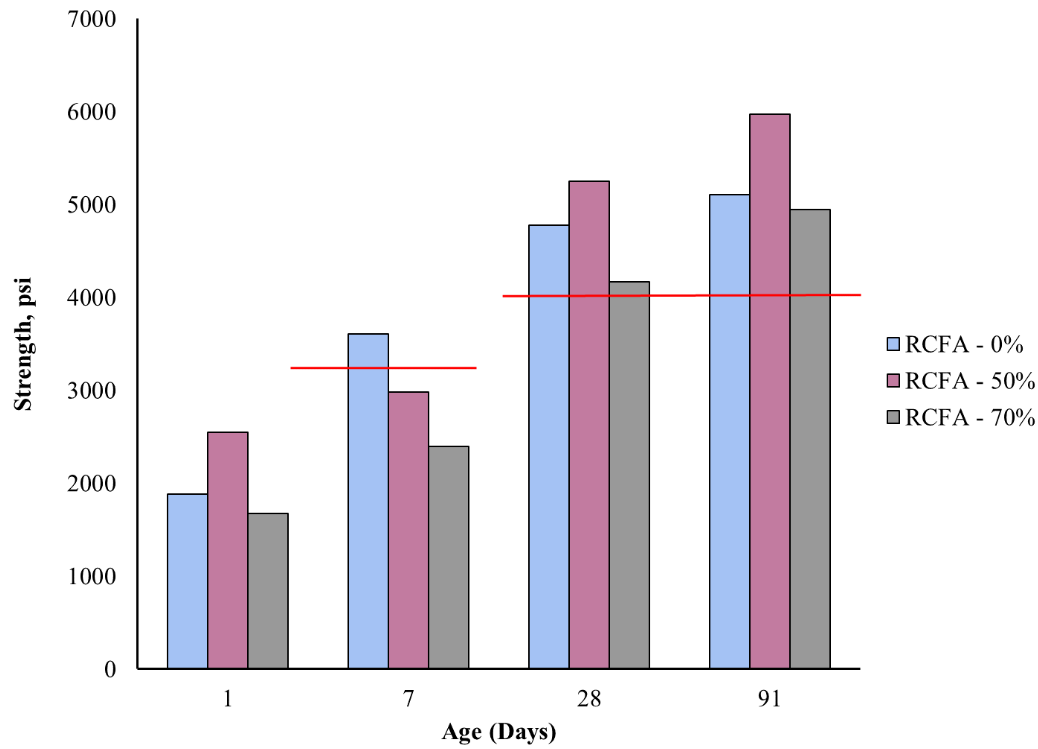

Figure 3.4: Compression strength results of portland cement concrete mixtures with varied RCFA contents.

Another round of compression testing was conducted on mixtures containing 20% Class F fly ash with RCFA contents ranging from 0-100%. The results of these test are illustrated in Figure 3.5. With the inclusion of 20% Class F Fly ash we see an increase in compressive strength across the board at seven days. Mixtures containing 70% and 100% RCFA do not reach the benchmark compressive strength of 3,200 psi at seven days. By 28 days the concrete mixtures containing 0-70% RCFA have surpassed the required compressive strength of 4,000 psi. The RCFA mixture containing 100% recycled fine aggregate is just shy of the 4,000 psi benchmark at 91 days.

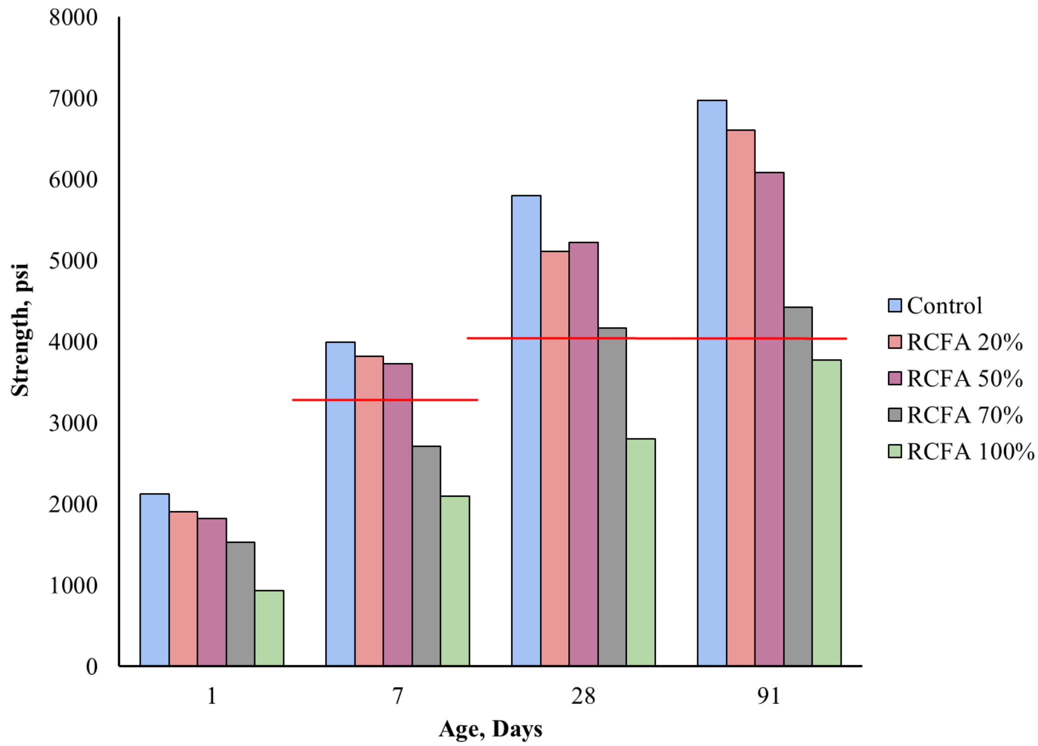

Figure 3.5: Compression strength results of concrete mixtures containing 20% Class F fly ash with varied RCFA contents.

Figure 3.6 shows compression testing results for concrete mixtures containing 35% Class C fly ash with RCFA contents ranging from 0-70%. The compressive strength results of these mixtures were significantly lower at seven days compared to the straight cement and Class F fly ash mixtures previously discussed. The mixture containing 50% RCFA reached the benchmark compressive strength of 4000 psi by 28 days, but it wasn't until the 91-day mark that the 70% RCFA mixture surpassed this same benchmark.

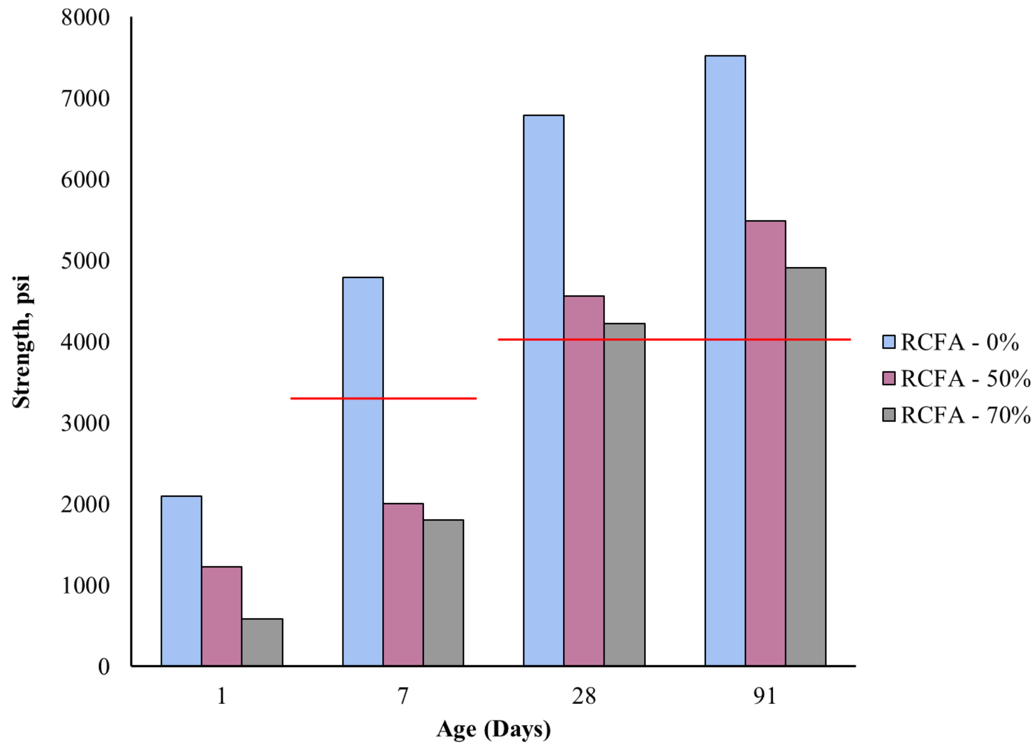

Figure 3.6: Compression strength results of concrete mixtures containing 35% Class C fly ash with varied RCFA contents.

Three concrete mixtures containing 20% class F fly ash and varied amounts of RCCA and RCFA were evaluated. One mixture contained 100% RCCA and 0% RCFA, another contained both 70% RCCA and 70% RCFA, and the third was produced with 100% RCCA and 70% RCFA. The concrete mixture containing 100% recycled coarse aggregate and 0% recycled fine aggregate met the compression strength thresholds at both 7 and 28 days whereas the other two mixtures containing both recycled coarse and fine aggregates were unable to meet either compression strength requirement. These results are illustrated in Figure 3.7.

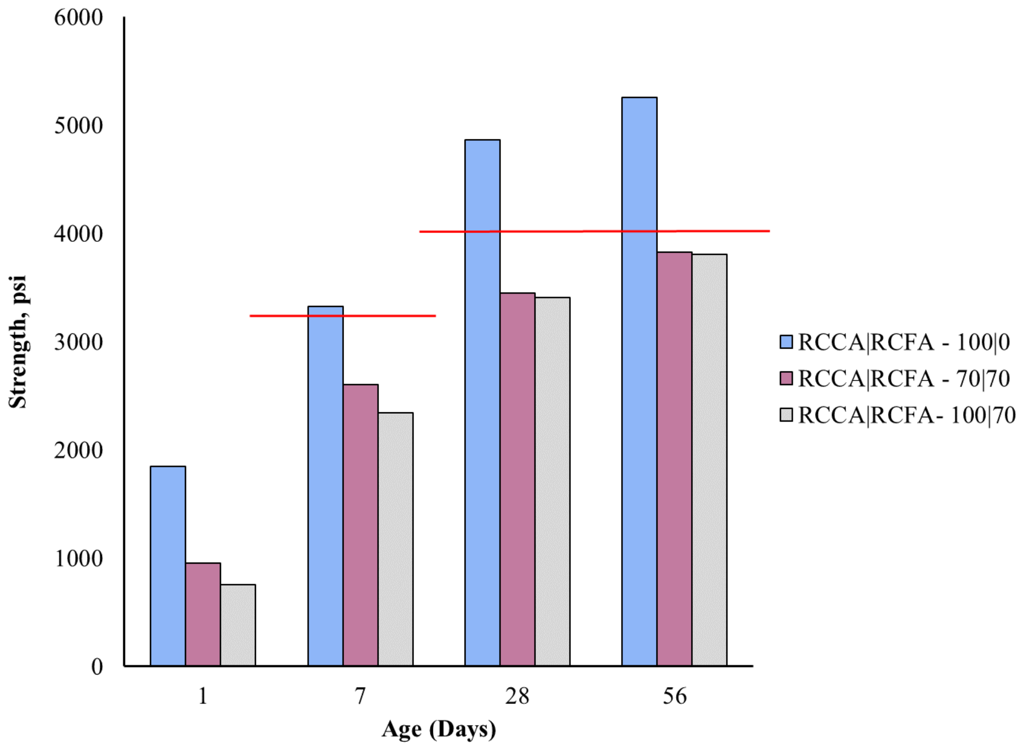

Figure 3.7: Compression strength results of concrete mixtures containing 20% Class F fly ash and varied amounts of RCCA and RCFA.

3.5.2. Splitting Tensile Strength

The splitting tensile strength of all RCFA mixtures was evaluated. Figure 3.8 shows the splitting tensile testing results for RCFA mixtures containing 0-70% RCFA in a straight portland cement concrete mixture. Figures 3.9 and 3.10 show the splitting tensile strengths for mixtures containing Class F fly ash and Class C fly ash, respectively. For all three cementitious types, the splitting tensile strength decreases with increased recycled concrete fine aggregate.

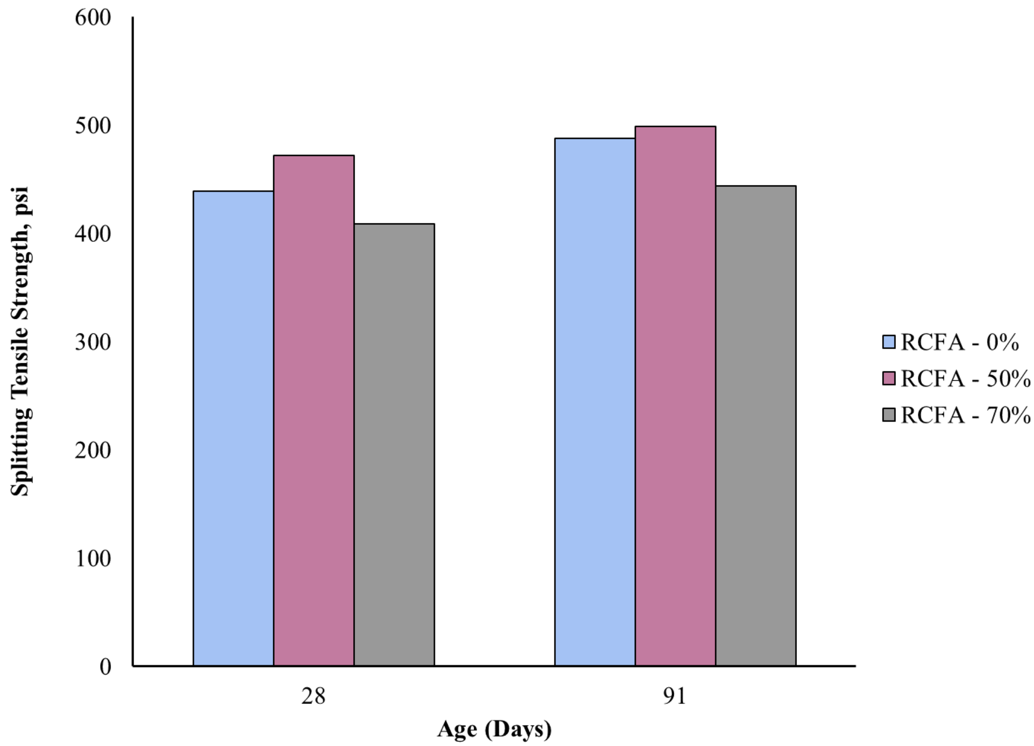

Figure 3.8: Splitting tensile data for Portland cement concrete mixtures containing 0-70% RCFA

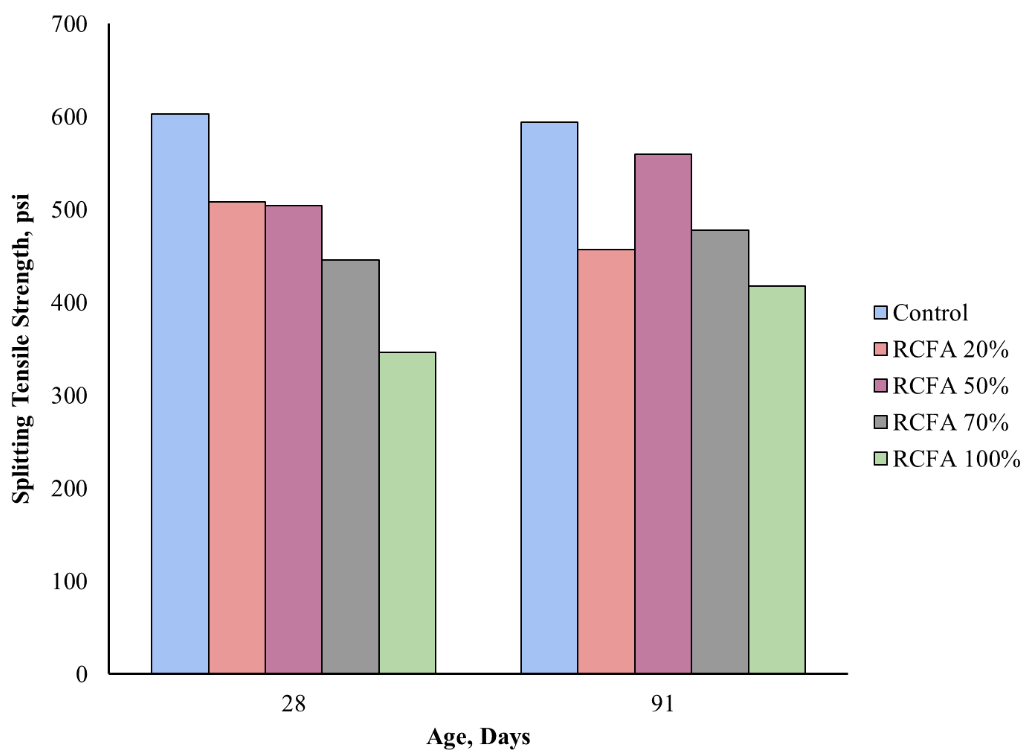

Figure 3.9: Splitting tensile data for mixtures containing 20% Class F fly ash and varied amounts of RCFA.

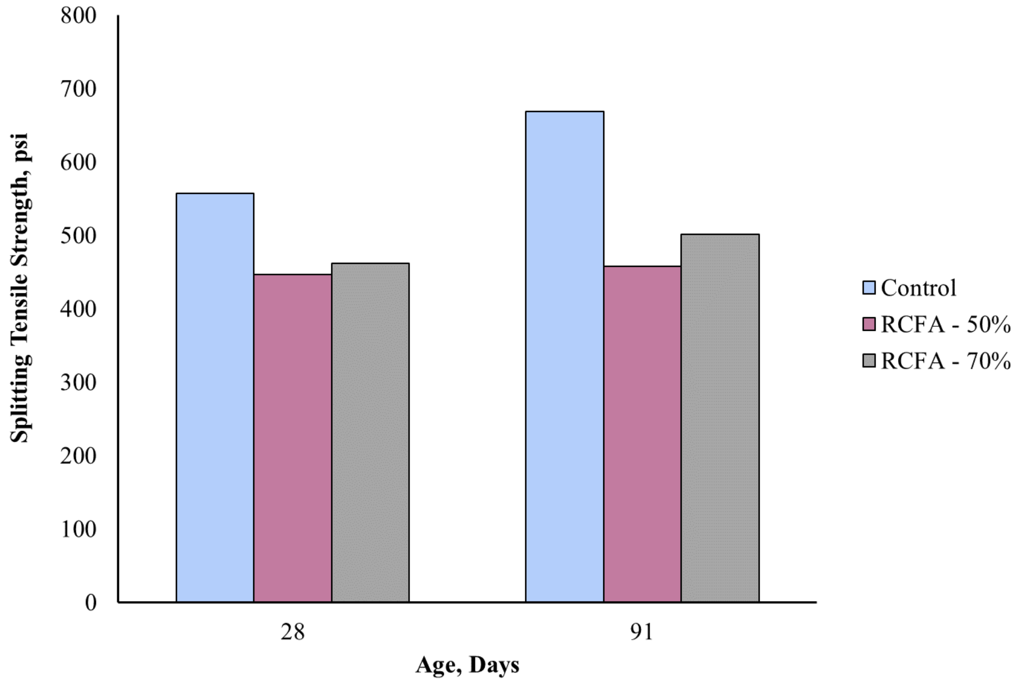

Figure 3.10: Splitting tensile data for mixtures containing 35% Class C fly ash and varied amounts of RCFA.

3.5.3. Elastic Modulus

The elastic modulus for the RCFA mixtures was evaluated and are shown in Figures 3.11-3.13. Figure 3.11 shows the elastic modulus results for RCFA mixtures containing 0-70% RCFA in a straight portland cement concrete mixture. Figures 3.12 and 3.13 show the splitting tensile strengths for mixtures containing Class F fly ash and Class C fly ash, respectively. The modulus for mixtures containing recycled concrete fine aggregate significantly decrease the concrete modulus. For the 100% RCFA in Figure 3.12, the elastic modulus is half compared to the 0% RCFA mixture. Mixtures at 50 and 70% RCFA also show the decrease in all cementitious combinations.

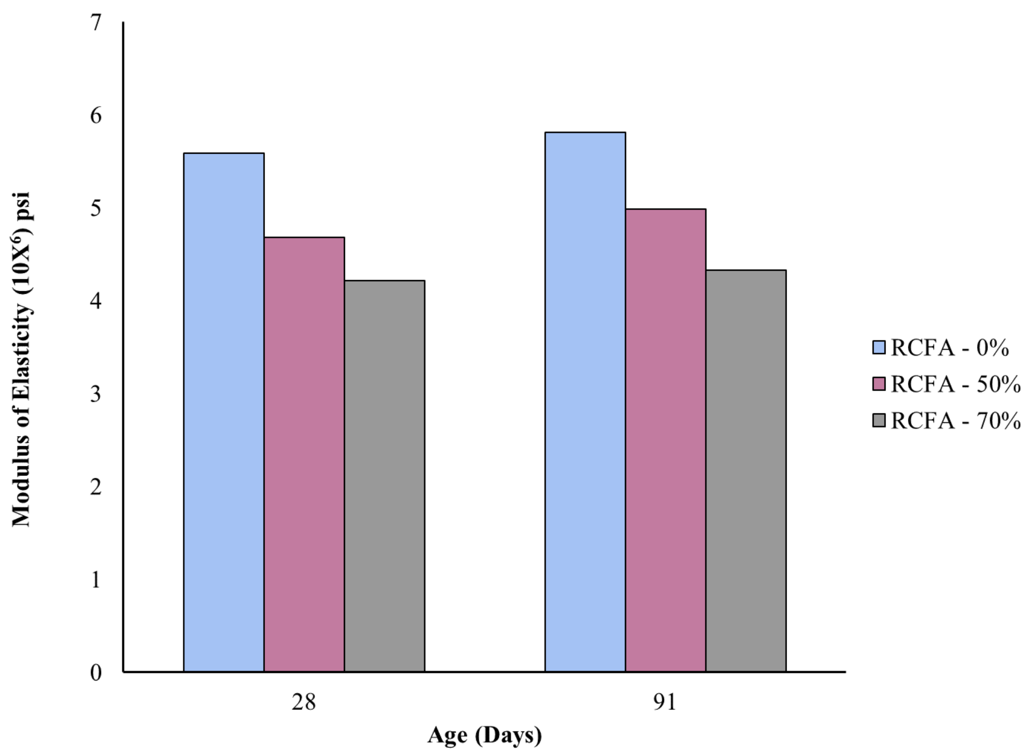

Figure 3.11: Modulus of elasticity data for Portland cement concrete mixtures containing varied amounts of RCFA.

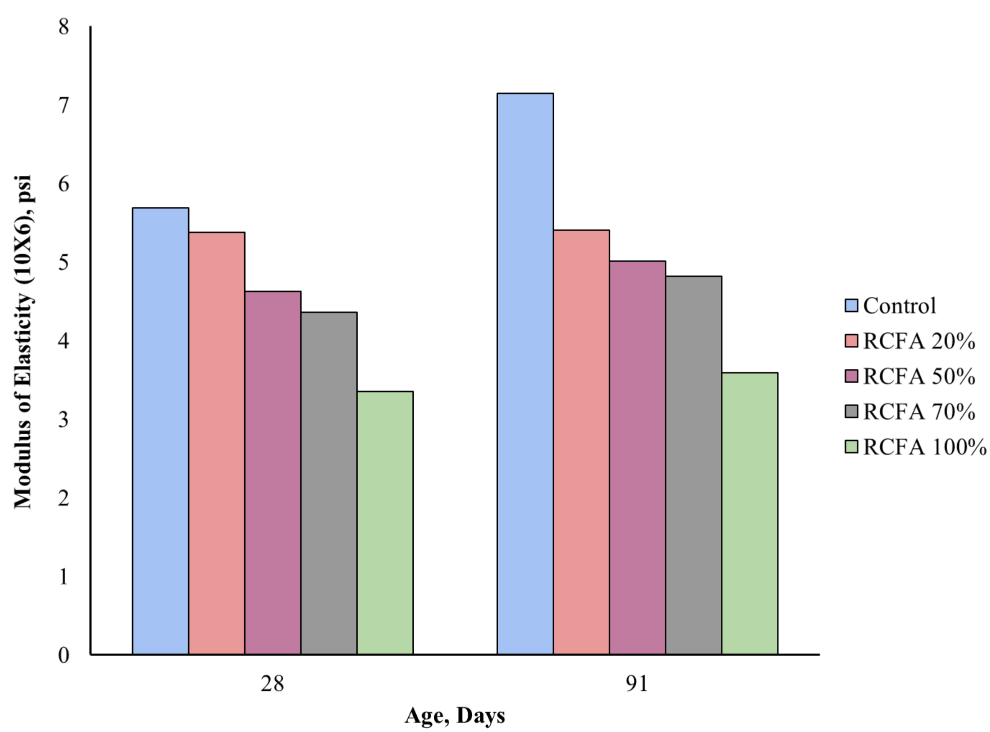

Figure 3.12: Modulus of elasticity data for mixtures containing 20% Class F fly ash and varied amounts of RCFA.

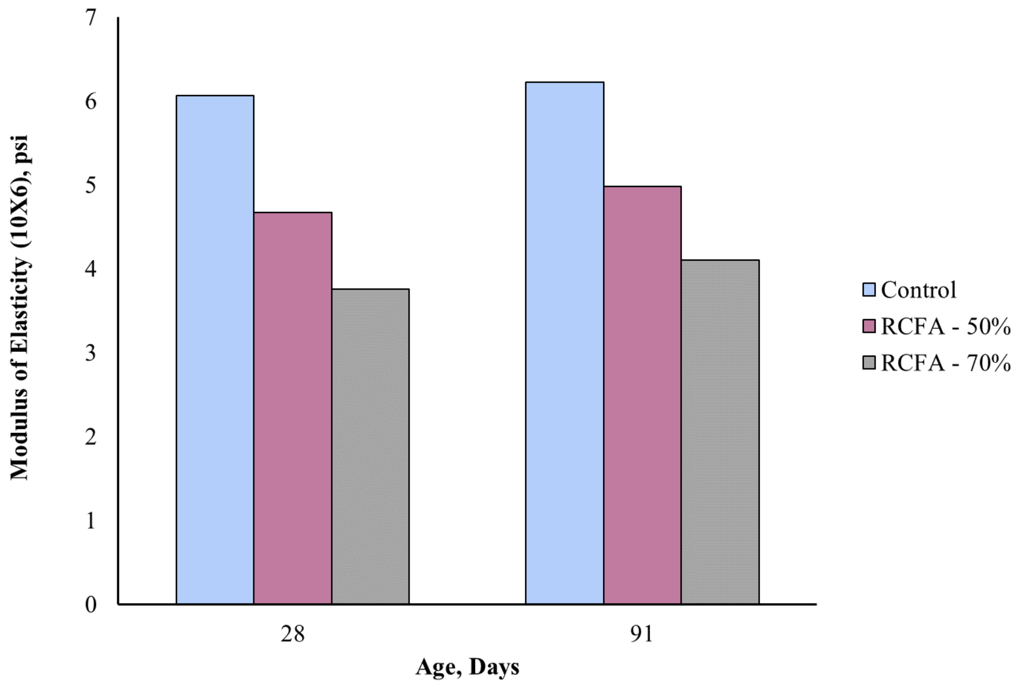

Figure 3.13: Modulus of elasticity data for concrete mixtures containing 35% Class C fly ash and varied amounts of RCFA.

3.5.4. Drying Shrinkage

There are several factors that affect drying shrinkage of concrete including: volume fraction of the hydrated cement paste, the elastic modulus of the aggregate, and the relative humidity of the environment. For typical concrete, the typical drying shrinkage values are in the range of 400 to 1000 microstrain. Since the volume instability occurs in the hydrated cement paste, minimizing the cement paste volume will result in lower drying shrinkage values (closer to 400 microstrain). Figures 3.14 through 3.17 show the drying shrinkage for mixtures containing recycled fine and coarse aggregates with different cementitious systems. Figure 3.14 shows the drying shrinkage in 100% portland cement mixtures. All the mixtures followed the same general trends. The rate of water loss is much greater during the first 28 days, leading to most of the drying shrinkage occurring in this period. However, the 50 and 70% mixtures had double the amount of shrinkage compared to the control mixture (0% RCFA).

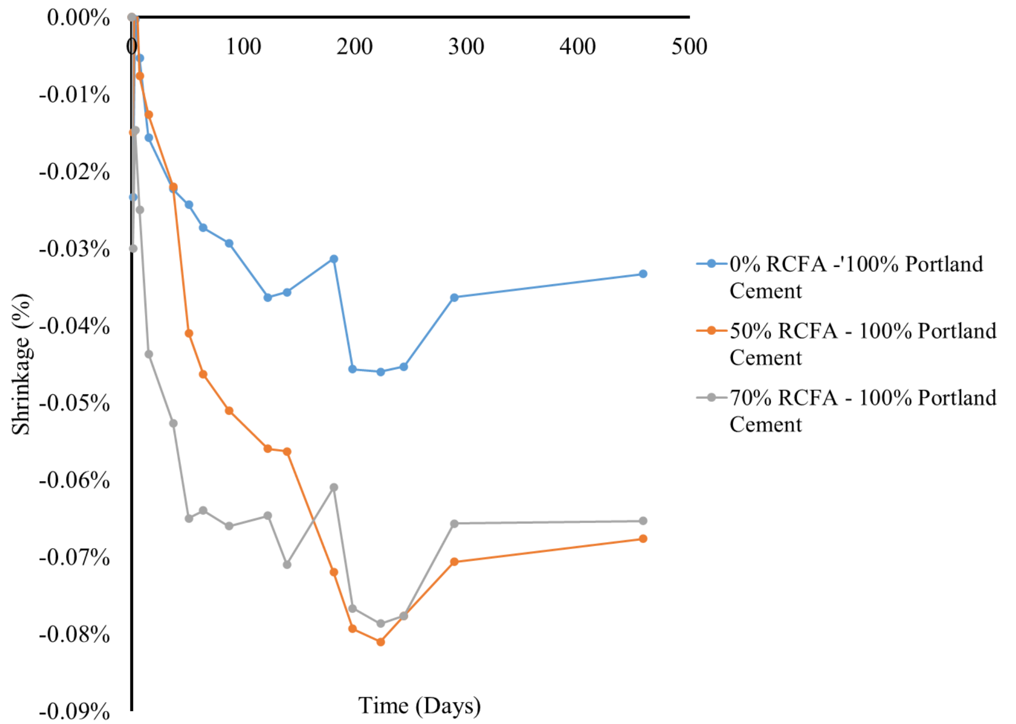

Figure 3.14: Drying shrinkage data for portland cement concrete mixtures with 0-70% RCFA.

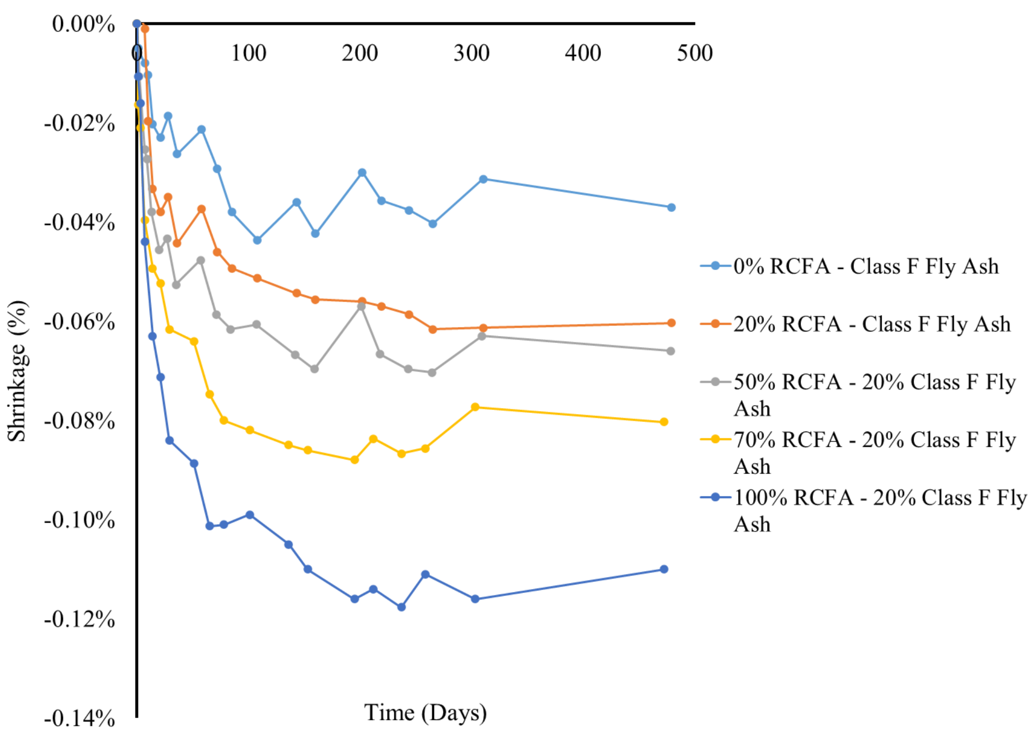

Figure 3.15: Drying shrinkage data for concrete mixtures containing 20% Class F fly ash with 0-100% RCFA

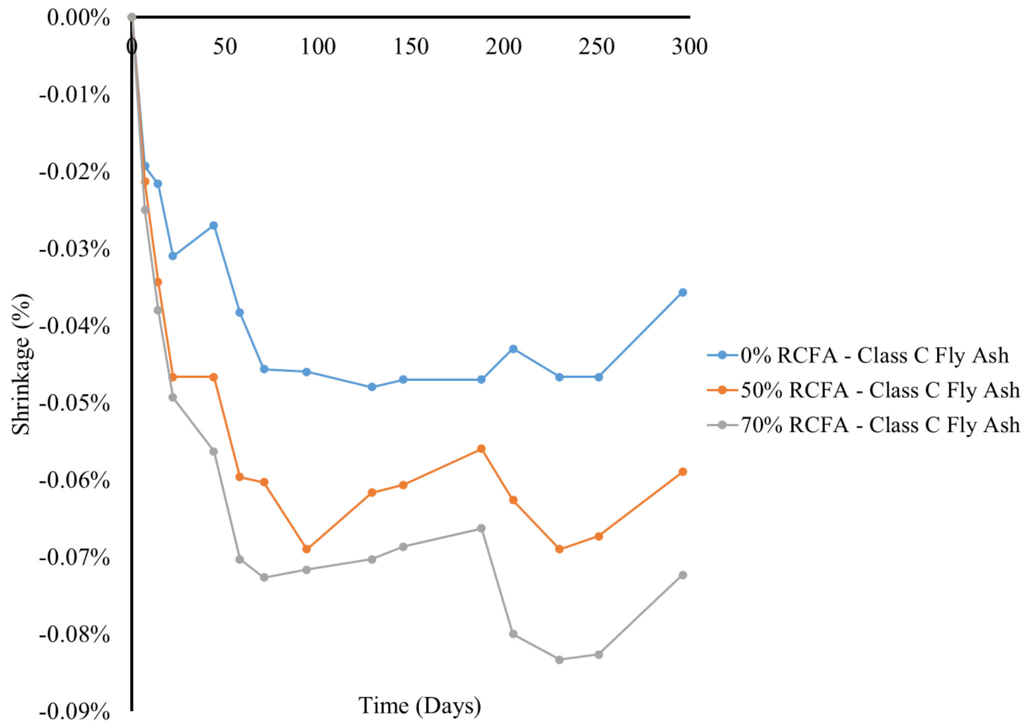

Figure 3.16: Drying shrinkage data for concrete mixtures containing 35% Class C fly ash with 0-70% RCFA

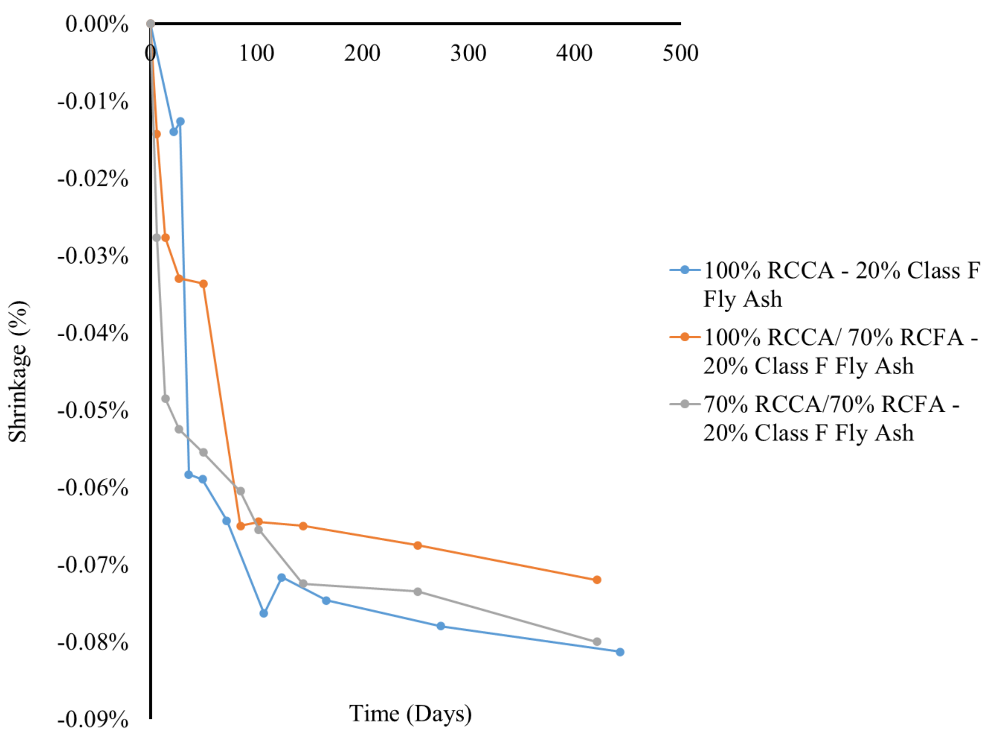

Figure 3.17: Drying shrinkage data for concrete mixtures containing 20% Class F fly ash with varied amounts of RCFA and RCCA.

3.5.4.1. Coefficient of Thermal Expansion

TxDOT test method Tex-428-A was used to evaluate the coefficient of thermal expansion (CoTE) for concrete mixtures containing 0 -100% of recycled fine aggregates and mixtures containing 100% recycled coarse aggregates. CoTE results were similar across the board for concrete mixtures produced with and without any amount of RCFA. Similarly, the CoTE results were comparable for mixtures produced with recycled coarse aggregates with and without the inclusion of recycled fine aggregates. These results indicate that the use of recycled concrete aggregates has little effect on the coefficient of thermal expansion for concrete mixtures. This data is shown in Figure 3.18.

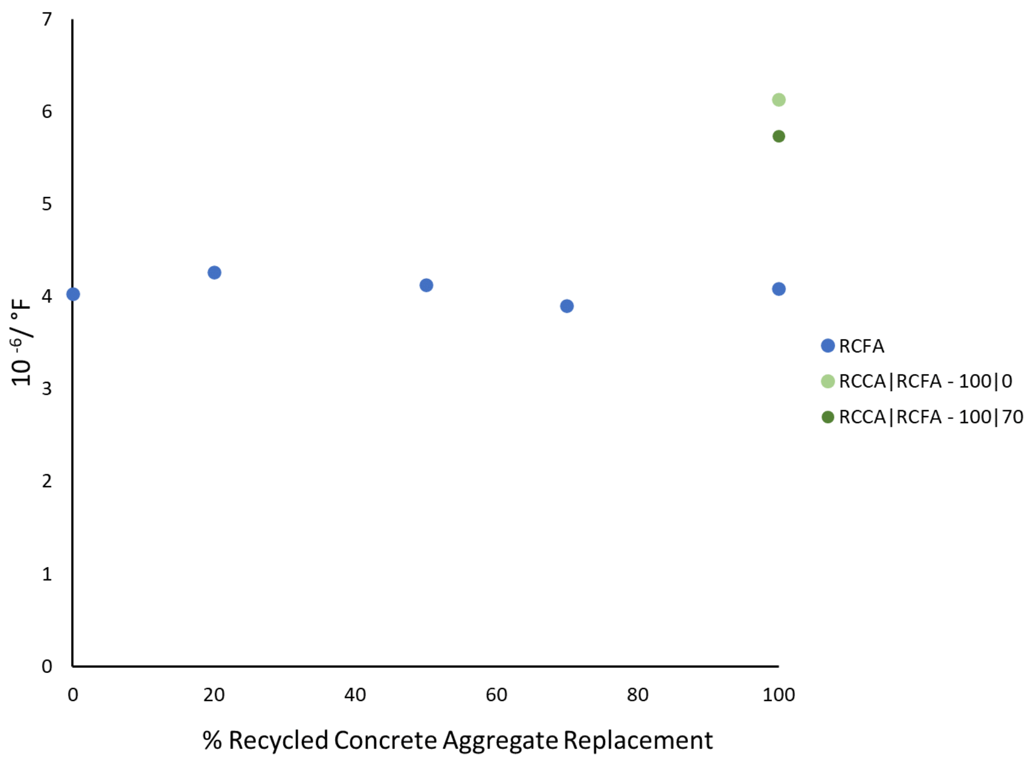

Figure 3.18: Coefficient of Expansion data for concrete mixtures containing varied amounts of recycled fine and coarse aggregates.

3.5.5. Durability of RCFA Concrete

3.5.5.1. Alkali-Silica Reaction

ASTM C1260 and AASHTO T 380 were both used to evaluate RCFA for aggregate reactivity. Figure 3.19 provides the aggregate reactivity for RCFA2. At 14 days, the expansion exceeded 0.10% which designates that the RCFA is considered potentially reactive. ASTM C1567 was used to show the possibility of mitigating the aggregate. The use of 20% Class F Fly ash was able to decrease the expansion below 0.10% at 14 days as shown in Figure 3.19.

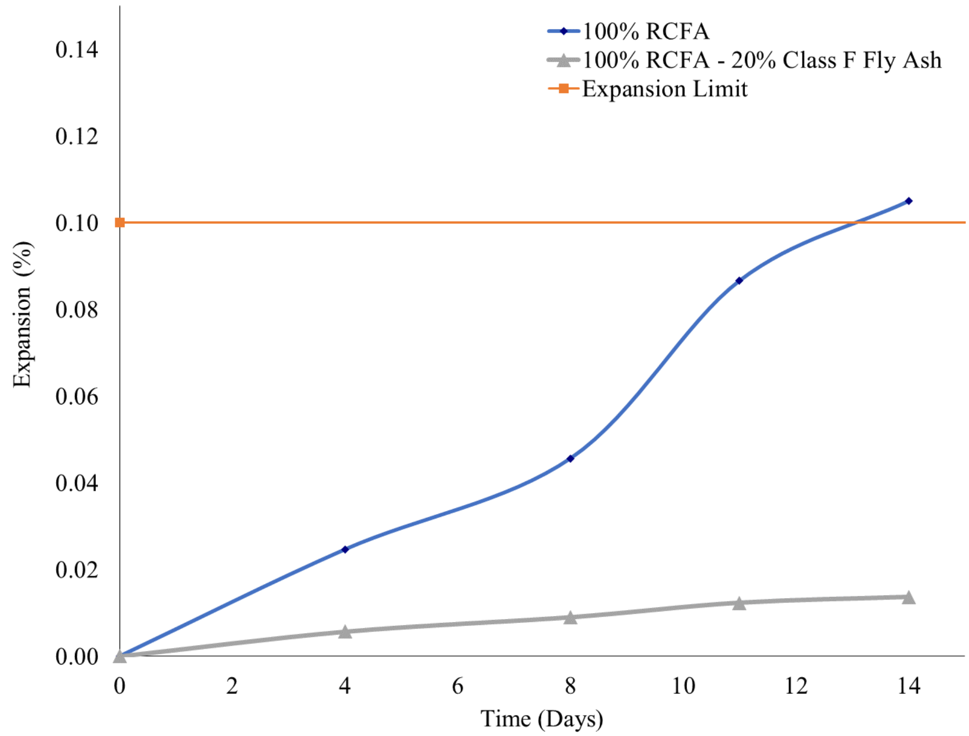

Figure 3.19: ASTM C1260 results for mortar mixtures containing 100% RCFA with and ASTM C1567 with 20% Class F fly ash.

A second set of ASR tests were conducted on large outdoor exposure blocks. The two exposure blocks were made with the same coarse and fine aggregates and had the same alkali loading. The only difference between the two exposure blocks was that one exposure block was only 1 month old and the second exposure block was 10 years old. The one-month exposure block had not begun expanding while the 10-year-old block had finished expanding to 1.5%. Both exposure blocks were crushed and sieved to fit the requirements of both ASTM C1260 and AASHTO R 80. In ASTM C1260, there was no difference between aggregate that had already expanded in the field compared to non-expanded exposure blocks as shown in Figure 3.20. AASHTO R 80 does shows a difference between the two recycled aggregates. Figure 3.21 shows that the non-expanded exposure block expands greater than the exposure block that had fully expanded. In both cases, the expansion is greater than the 0.02% expansion limit set in AASTHTO R 80.

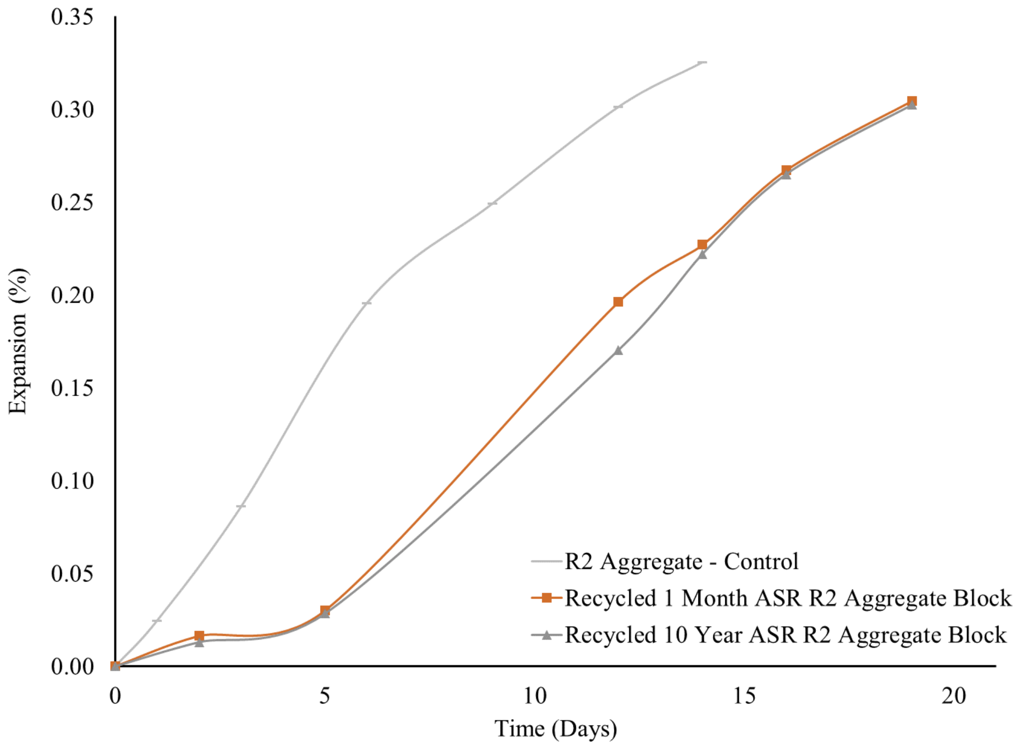

Figure 3.20: ASTM C1260 results for mortar mixtures containing 100% RCFA from recycled concrete exposure blocks.

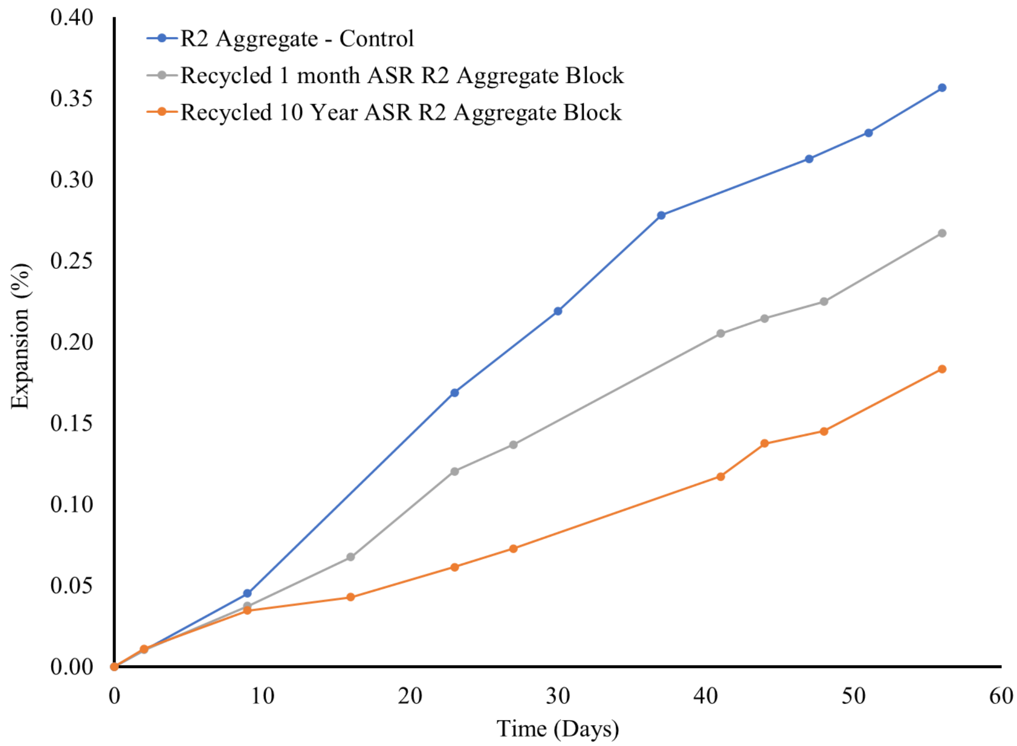

Figure 3.21: MCPT results for concrete mixtures made from crushed concrete exposure blocks with varied levels of expansion due to ASR prior to crushing.

3.5.5.2. External Sulfate Attack

ASTM C1012 testing was conducted to evaluate the sulfate resistance of mortar bars with 0%, 50% and 100% RCFA with Class C fly ash. The mixtures containing 0% and 20% Class C fly ash failed within one year. All three mixtures containing 40% Class C fly ash performed similarly throughout the length of the test and expansion was well below the expansion limit of 0.1% at one year as shown in Figure 3.22. Good sulfate resistance of RCFA mixtures was dependent on the inclusion of class C fly ash rather than RCFA content.

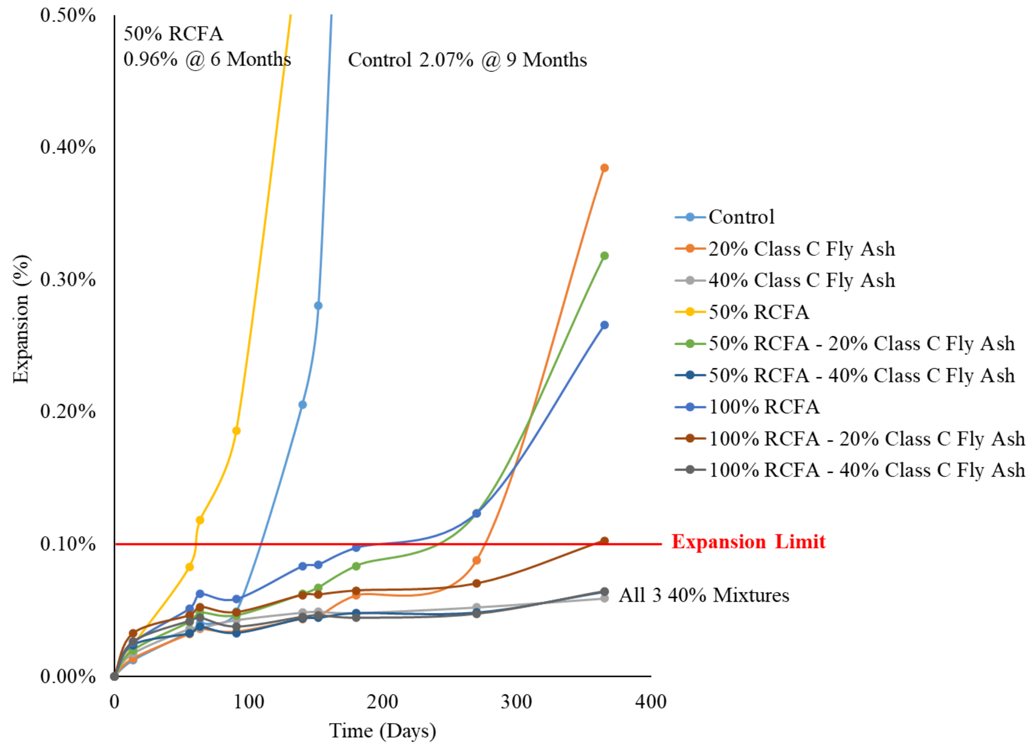

Figure 3.22: ASTM C1012 results for control and RCFA mixtures of various replacement levels.

3.5.5.3. Delayed Ettringite Formation

Delayed Ettringite Formation (DEF) is not thought to be an issue in concrete pavements. However, it was included in the testing regime to see how recycled concrete fine aggregate would perform if concrete did get to elevated temperatures. The Kelham heating regime was used to heat treat the samples and the DEF expansion results are shown in Figure 3.23. The 100% RCFA mixture began to expand prior to the control mixture and had a higher expansion until the bars were not readable after the 9 month measurement.

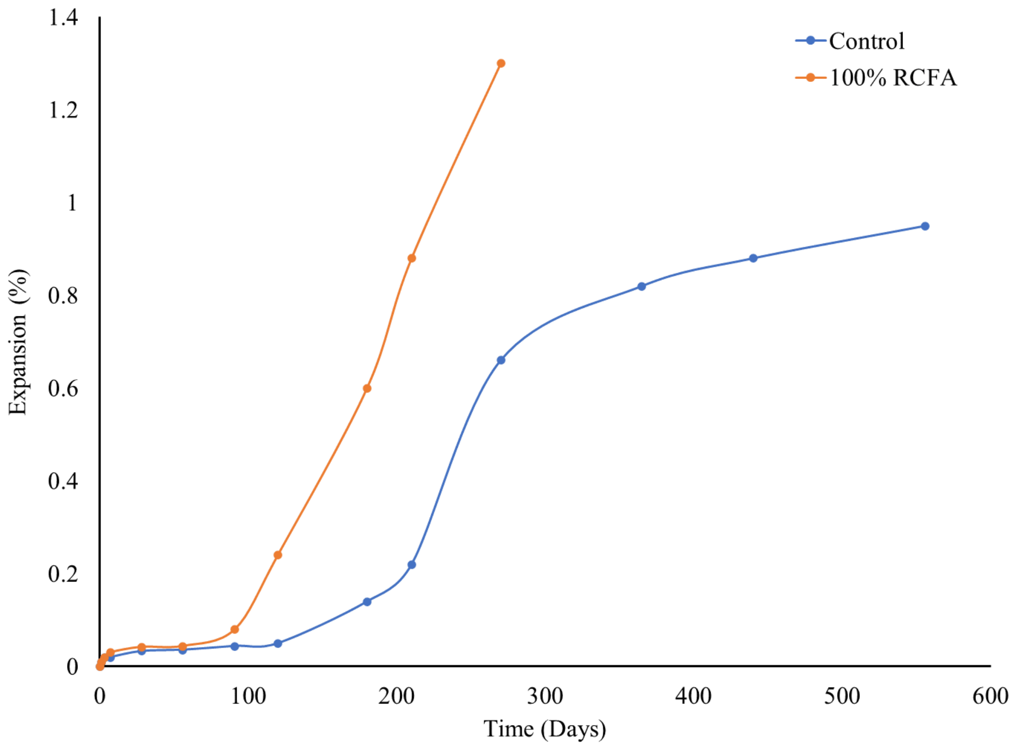

Figure 3.23: Kelham Testing for the potential of delayed ettringite formation.

3.5.5.4. Chloride Diffusion

Samples with recycled concrete fine aggregate (RCFA) and recycled concrete coarse aggregate (RCCA) were cast and placed in sodium chloride solution for 56 days. The samples were removed from the solution and sent for analysis using µXRF. Figure 3.24 shows the chloride ingress for the different samples. Overall, the RCFA mixtures provided much less chloride ingress compared to the RCCA mixtures. The results were negligible between mixtures containing recycled concrete fine aggregate.

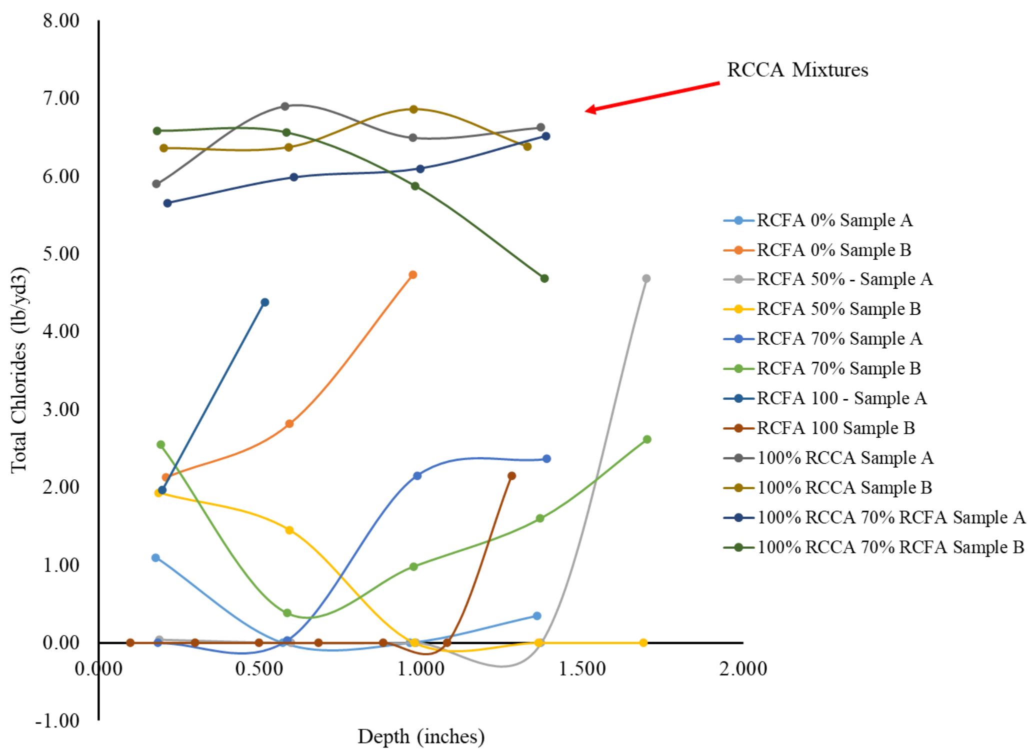

Figure 3.24: Chloride ingress of RCCA and RCFA samples using μXRF.

3.5.5.5. Surface Sorptivity

ASTM C1585 was employed to evaluate the rate of absorption (sorptivity) of water by concrete mixtures produced with 20% Class F fly ash and various amounts of recycled fine and coarse aggregates. The results are shown in Figure 3.25. The control mixture which contained 0% RCFA performed similarly to the mixture containing 0% RCFA and 100% RCCA. Interestingly, the mixture containing 50% RCFA had the lowest rate of absorption, lower even than the control, and data indicates that the absorption rate increases with increased RCFA content. However, the mixture with the highest rate of absorption was the mixture containing 100% RCCA and 70% RCFA which is inconsistent with the rest of the data set.

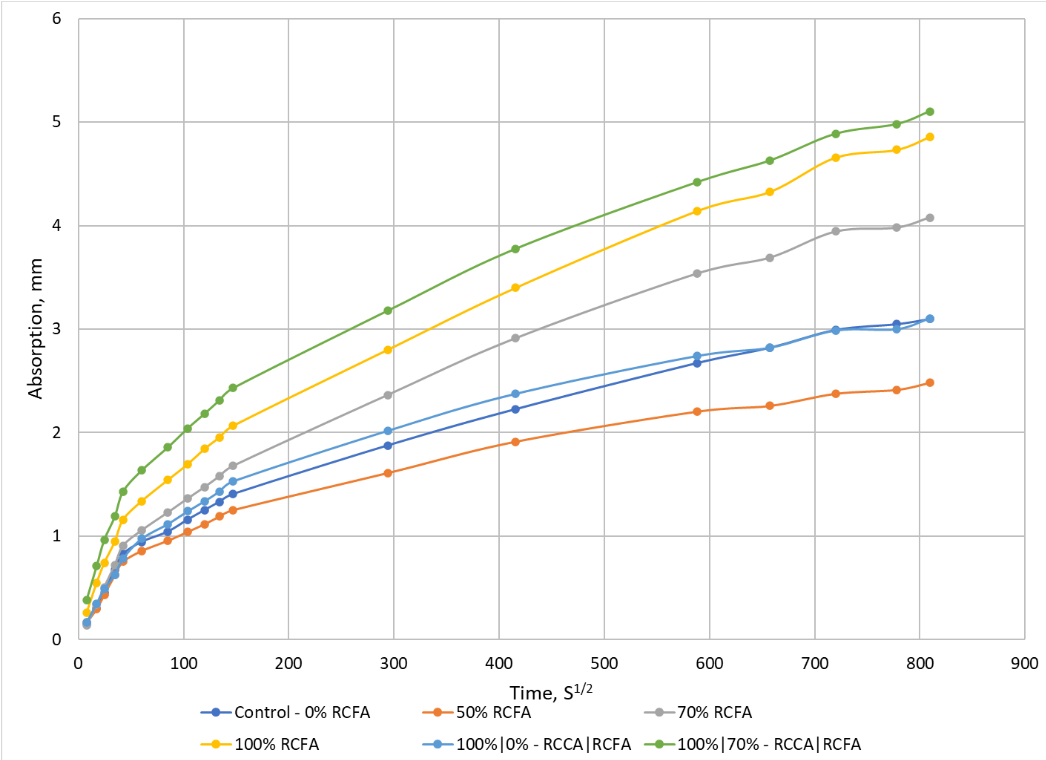

Figure 3.25: Sorptivity Data for concrete mixtures containing 20% Class F Fly Ash with various amount of RCFA and RCCA.

3.5.5.6. Carbonation

The depth of carbonation was measured on concrete prisms after 18 months of indoor exposure at 73°F and 50% RH. Figures 3.26 through 3.29 provide the carbonation depth on the different sets of cementitious mixtures containing different amounts of recycled concrete fine aggregates. Generally, there is a slight increase in depth of carbonation with increased RCFA content. The recycled coarse aggregate in Figure 3.27 does show a higher depth of carbonation when compared to the control and other recycled concrete fine aggregate mixtures.

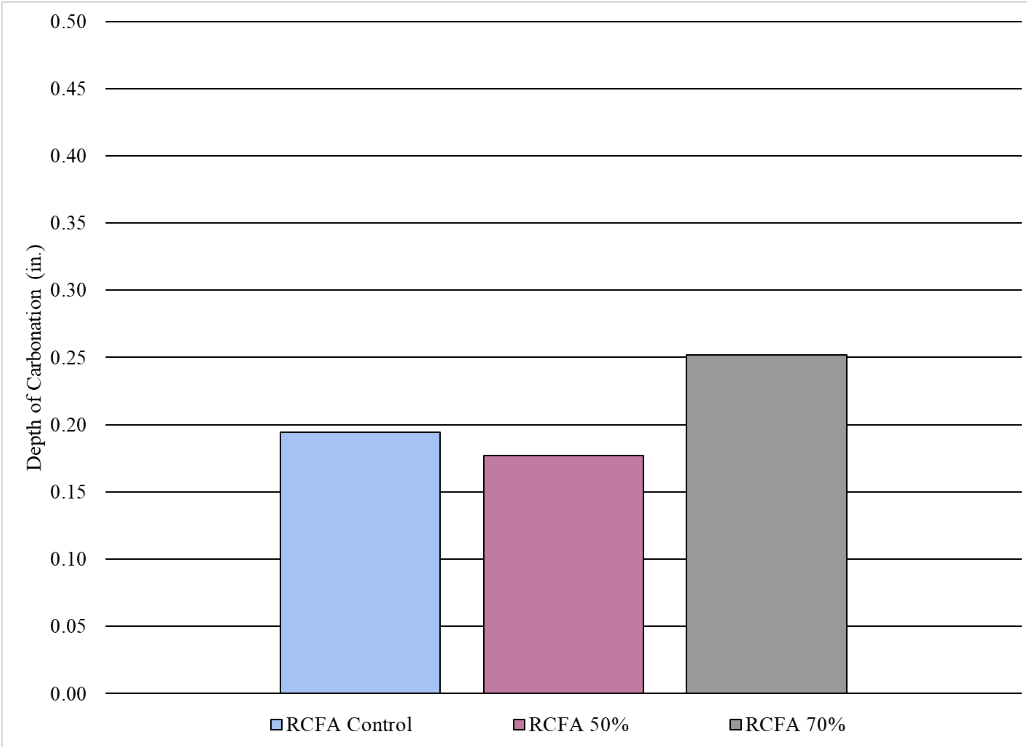

Figure 3.26: Depth of carbonation data for portland cement concrete mixtures containing 0-100% RCFA

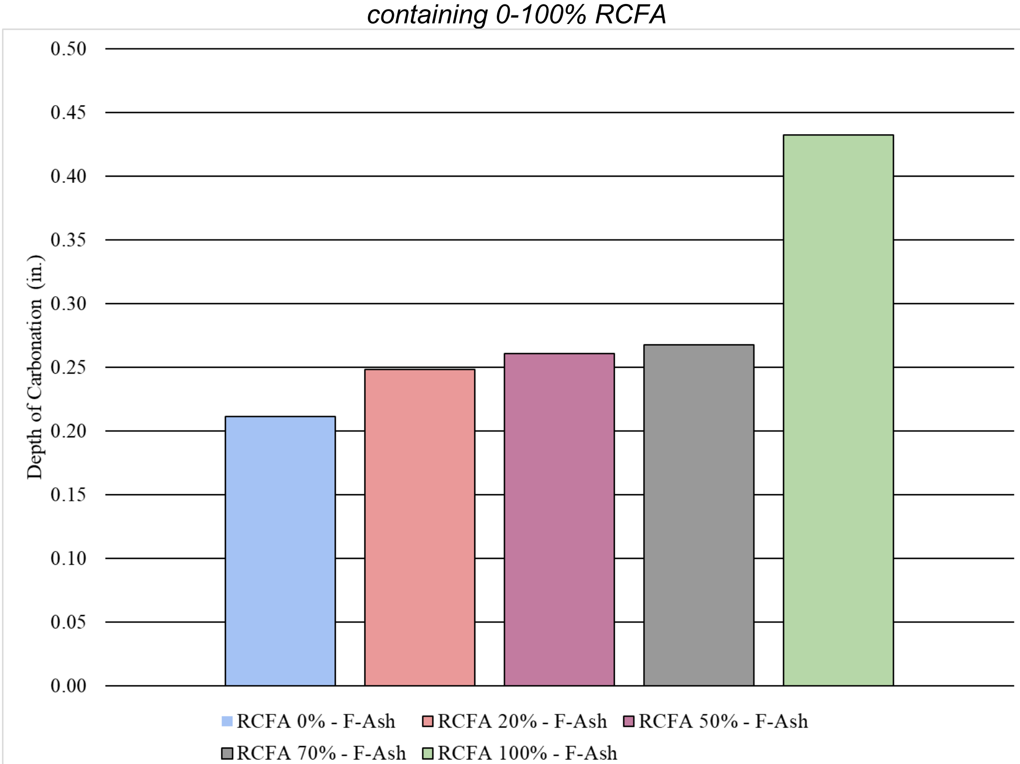

Figure 3.27: Depth of carbonation data for concrete mixtures containing 20% Class F fly ash with 0-100% RCFA

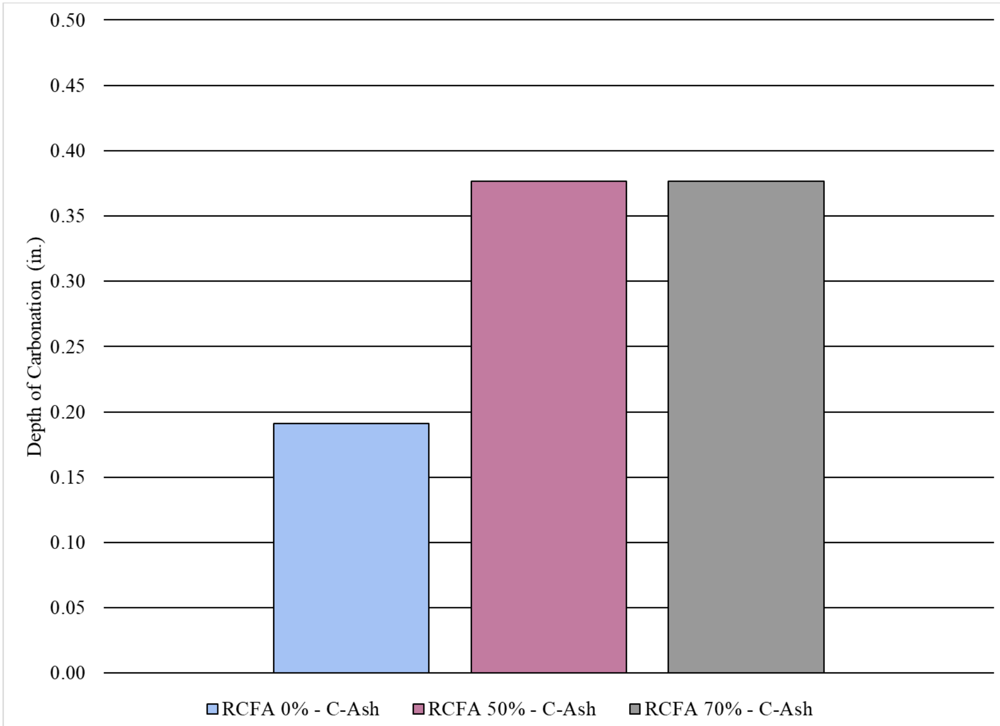

Figure 3.28: Depth of carbonation data for concrete mixtures containing 35% Class C fly ash with 0-70% RCFA

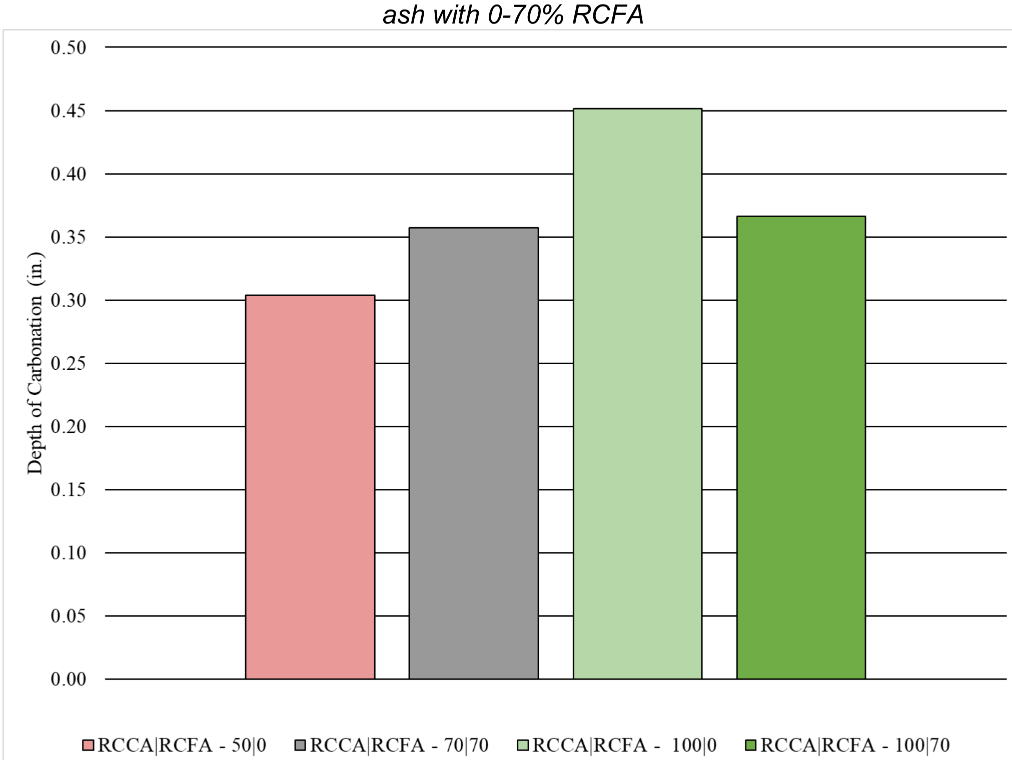

Figure 3.29: Depth of carbonation data for concrete mixtures containing 20% Class F fly ash with varied amounts of RCFA and RCCA.

3.5.5.7. Freezing and Thawing

ASTM C666 was conducted on a set of mixtures containing recycled concrete fine aggregates to evaluate their freeze-thaw resistance. Figure 3.30 shows the mass change of the mixtures during the test and Figure 3.31 provides the dynamic modulus of the mixtures. As the recycled concrete fine aggregate increases there is a significant drop in performance. None of the recycled concrete fine aggregate mixtures were able to last 300 cycles in the test. The mixtures were air-entrained however the spacing of air bubbles may not be adequate for mixtures with recycled concrete fine aggregate.

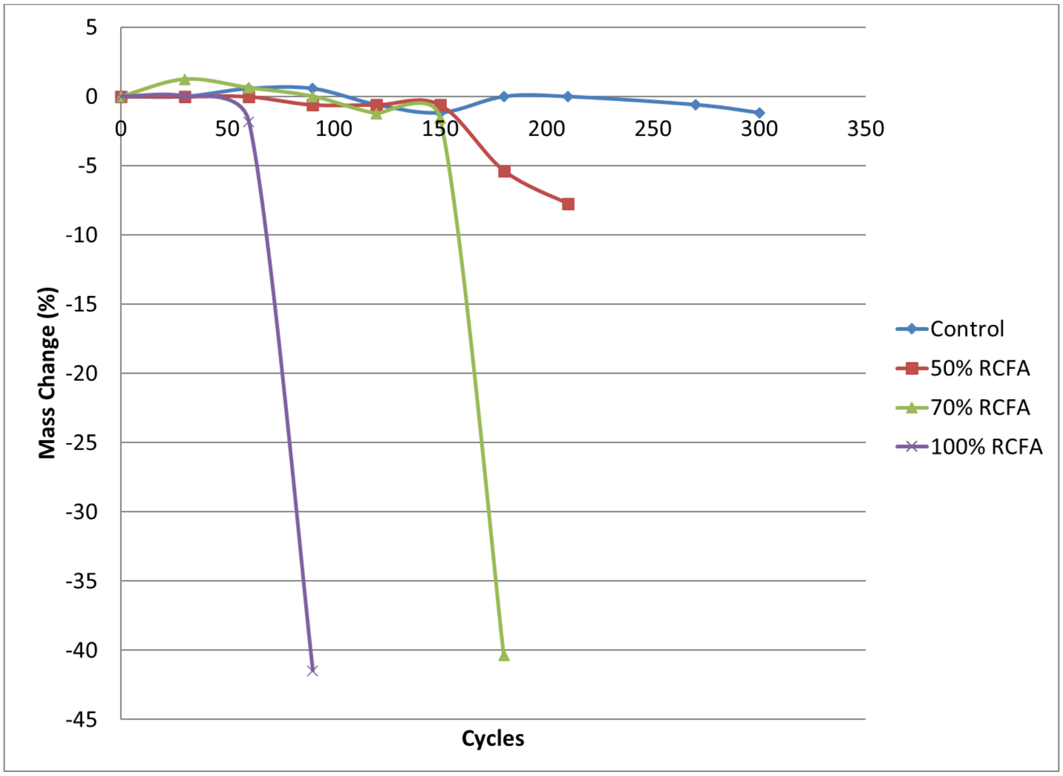

Figure 3.30: Mass loss of concrete mixtures containing 0-100% RCFA subjected to freeze/thaw cycles in ASTM C666.

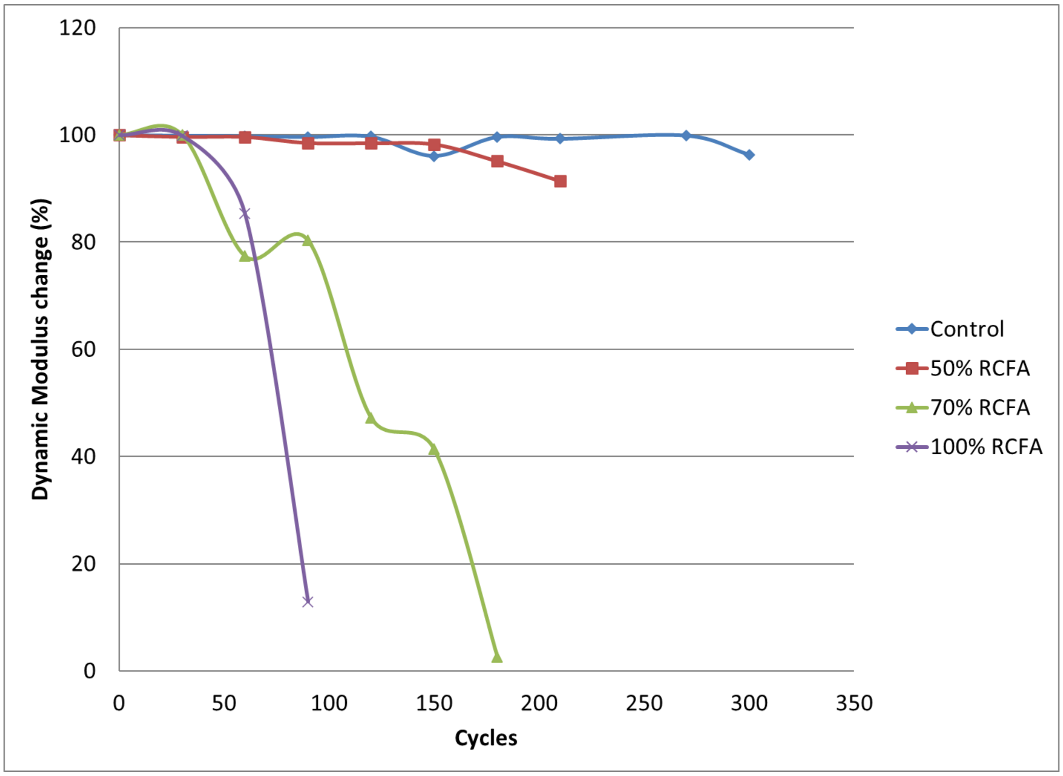

Figure 3.31: Dynamic modulus of concrete mixtures containing 0-100% RCFA subjected to freeze/thaw cycles in ASTM C666.

3.5.5.8. Salt Scaling

ASTM C672 was used to evaluate resistance to scaling of a horizontal concrete surface exposed to freezing-and-thawing cycles in the presence of deicing chemicals. Samples from concrete mixtures containing 0-100% RCFA were subjected to up to 50 freeze thaw cycles while submerged in calcium chloride solution. After 5, 10, 15, 25, and every 25 cycles thereafter the surface of the concrete samples was rated visually in accordance with the following scale in Table 3.13.

Table 3.13: Visual Rating of Concrete Surface per ASTM C672

Rating	Condition of Surface
0	No scaling
1	Very slight scaling (3mm [1/8in.] depth, max, no coarse
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

Visual interpretation of the surface conditions of concrete samples provides qualitative results that can aid in predicting durability trends. Results from this test method are subjective depending on each operator's visual interpretation. Potential for salt scaling increased slightly with the inclusion of RCFA as shown in Figure 3.32. Less than very slight scaling was noted in the mixture containing 70% RCFA after 10 freeze/thaw cycles, and after 20 cycles all three mixtures containing RCFA showed very light scaling (less than 1/8") with no coarse aggregate exposed. After 30 cycles the control and all RCFA mixtures showed the same degree of very slight scaling. The mixtures containing RCFA showed slight signs of scaling earlier in the test, but ultimately all mixtures showed low potential for durability issues related to salt scaling.

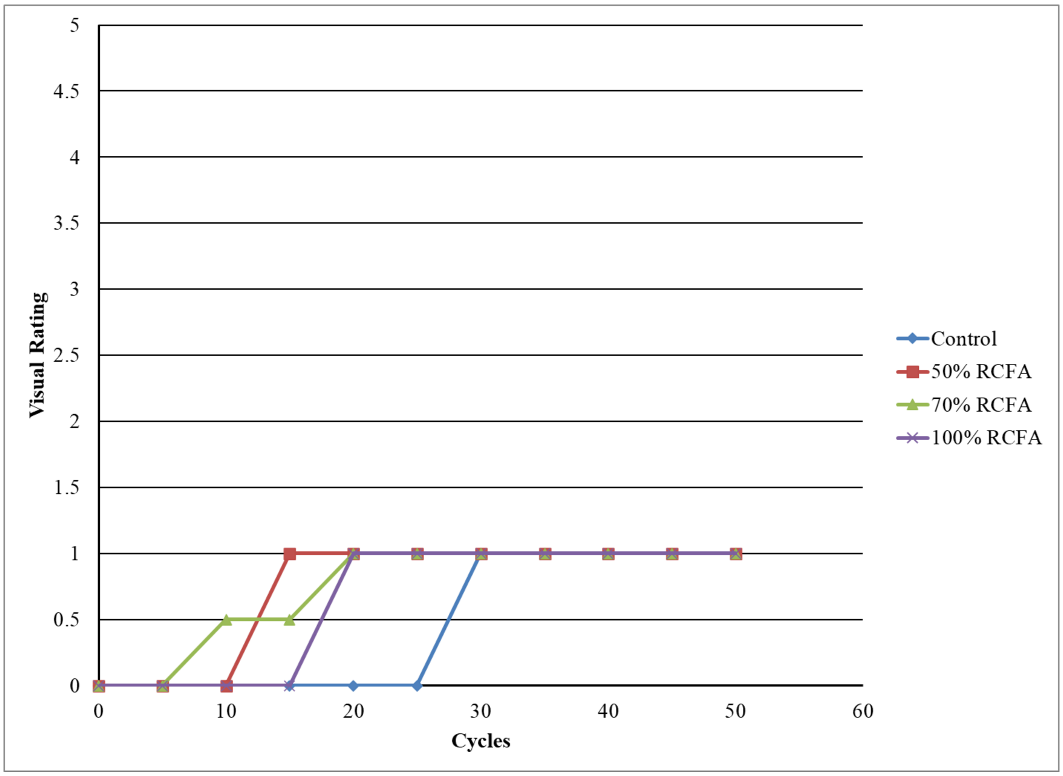

Figure 3.32: Results of visual rating of concrete mixtures containing 0-100% RCFA subjected to freeze/thaw cycles per ASTM C672.

3.6. Summary

The results of a comprehensive laboratory evaluation have shown that recycled concrete aggregates, RCFA and/or RCCA, can be used in relatively high proportions to produce concrete consistent with requirements for TxDOT Class P concrete. The primary findings from this laboratory evaluation were implemented in a full-scale CRCP field trial, as described next in Chapter 4.

Chapter 4. Field Evaluation of RCFA

4.1. Introduction and Overview of Test Sections

Applying the knowledge and experience gained in the laboratory evaluations, a field trial was performed to test the performance of recycled concrete aggregates in TxDOT Class P paving concrete mixtures. The field trial took place on September 12, 2022 and included a total trial section of about a half a mile of 9” thick, 14’ wide continuously reinforced concrete pavement (CRCP) frontage road. Figure 4.1 shows the location of the field trial in Sealy, TX. The trial was performed on the Eastbound frontage road of I-10 between Beckendorff Road and Pyka Road. Paving started at about 8:45 am and ended at about 5:15 pm.

Figure 4.1: Location of field trial in Sealy, TX

Figure 4.2 shows the overall 2500-ft field trial. It was originally intended to have five individual test sections of equal 500 ft length, including two sections containing recycled concrete coarse aggregate (RCCA). However, due to lack of availability of RCCA on site, it was decided to focus on the primary objective of increasing the amount of RCFA used in Class P paving mixtures. RCFA contents of 50 and 70 percent were included in the field trial and compared to the standard contractor Class P concrete. More specific information on the materials and mixture proportions used in the field trial, as well as information on instrumentation, construction, and performance monitoring are described in the remainder of this chapter.

Figure 4.2: Length and estimated concrete volume for each of the three test sections

4.2. Instrumentation and Construction of Test Sections

4.2.1. Instrumentation of Test Sections

Figure 4.3 shows a photo of the installation of vibrating wire gauges, which were installed at the midpoint of each of the originally planned 500 ft sections. Five separate data acquisition stations were set up at the midpoint of each of the 500 ft sections, with the wiring routed below grade from the six vibrating wire gauges installed at each monitoring station, as illustrated in Figure 4.4. At each station, gauges were installed at specific distances from the asphalt-treated base, as shown in the photo on the right in Figure 4.3. For each of the six vibrating wire gauges, temperature and strain values were continuously measured and recorded from the time of construction through the present.

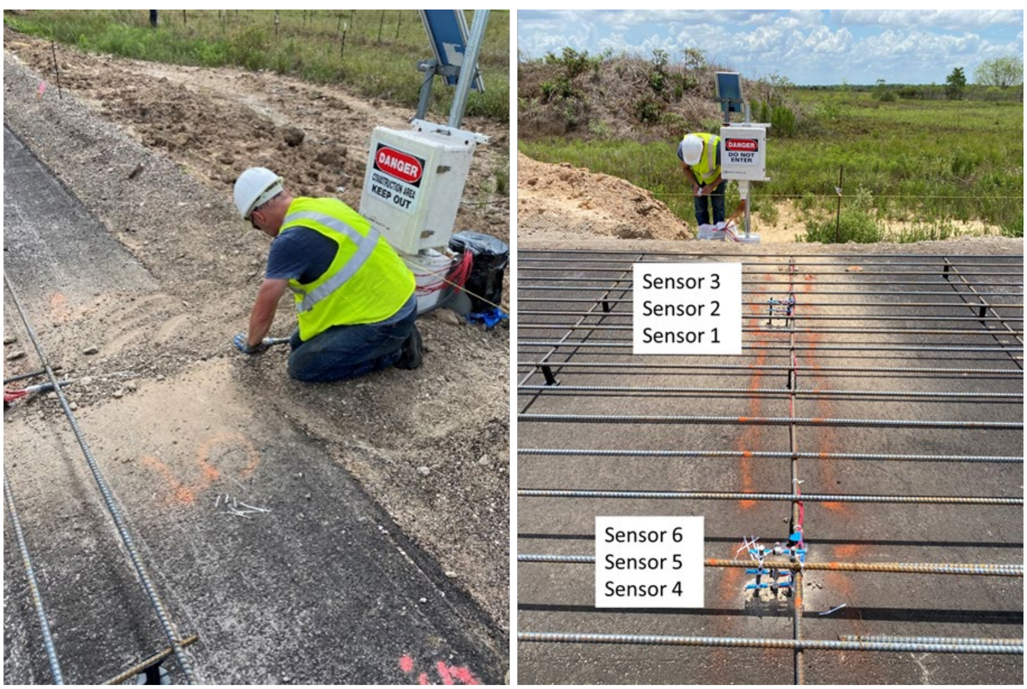

Figure 4.3: Installation of Vibrating Wire Gauges for the measurement of strain and temperature

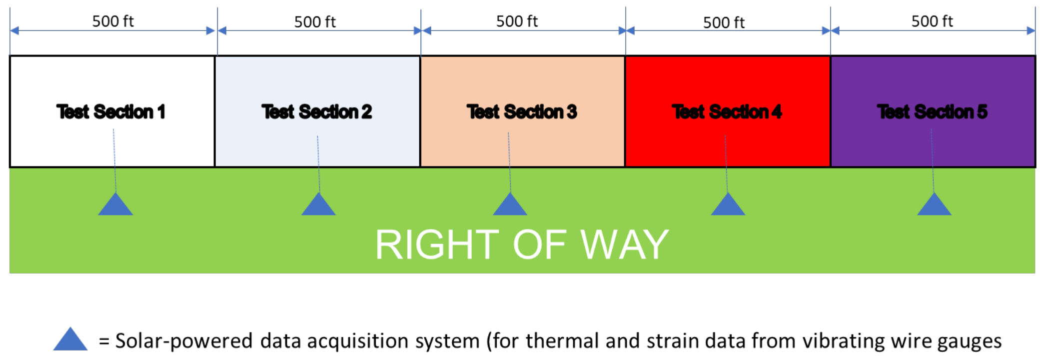

Figure 4.4: Intended test section lengths and associated locations for data acquisition stations, based on original field trial plan.

4.2.2. Construction of Test Sections

A stockpile of RCFA was procured and stored at the job site concrete plant (located at I-10 and Pyka Road). The RCFA was conditioned to a moisture content of 10-15 percent, which was found to be optimal in laboratory testing. Due to the moisture content and higher absorption, the contractor faced difficulties in processing the material, specifically, the RCFA got hung up on the chutes feeding the conveyor belt. Significant efforts were undertaken by the contractor to rectify the problem and were able to modify the chute to facilitate the loading of the RCFA. Because this took significant time and effort, the control section ended up being longer than planned but such is the reality with field trials. Once the above issue was handled, over 400 ft of 50% RCFA and 300 ft of 70% RCFA was successfully placed, with only minimal impact (if any) on paving operations. Figure 4.5 shows the actual configuration of the as-built test sections, along with the location of the data acquisition systems. Note that two data acquisitions were kept for the control section but the third station was removed for future use. The test sections containing RCFAs each had a data acquisition station within those test sections.

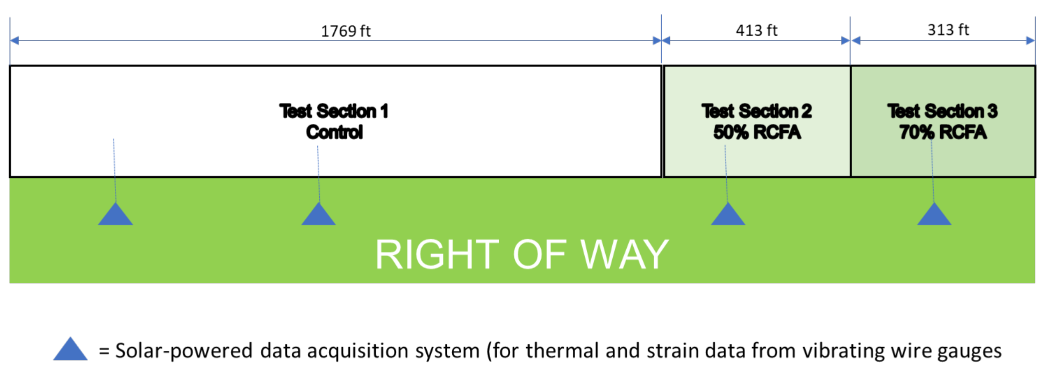

Figure 4.5: Actual length of the constructed test sections and location of data acquisition stations

The mixture proportions used in the three test sections are detailed in Table 4.1 The control mix was the contractor's everyday mix being used on the I-10 project in and around Sealy, TX. A high-range water reducer (polycarboxylate) was used to adjust for variations in workability. The total cementitious materials content was maintained below the 520 lbs/yd^3 limited imposed by TxDOT on Class P concrete.

Table 4.1: Materials and mixture proportions used in test sections

Mixture	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Recycled Concrete Fine Aggregate (lb/yd^3)	Cement (lb/yd^3)	Fly Ash (lb/yd^3)	Water (lb/yd^3)
Control	1847	1502	0	369	92	234
50% RCFA	1728	712	568	416	104	234
70% RCFA	1697	437	813	416	104	234

The results of on-site fresh concrete property testing are shown in Table 4.2. Similar to laboratory testing, the inclusion of RCFAs tends to reduce the air content in fresh concrete. No adjustments were made by the contractor as the location does not require air entrainment for frost protection. Sampling for fresh concrete testing was done as close to the data acquisition locations as possible to best reflect the concrete in that proximity.

Table 4.2: Fresh concrete properties measured on site (sampled near locations of data acquisition stations

Mixture	Time sampled (time when paving reached strain gauge for test section)	Slump (in)	Air (%)	Unit Weight (lb/ft^3)	Temperature (°F)
Control	10:02 am	0.5"	5.3%	144.0	82
50% RCFA	3:10 pm	0"	3.3%	144.7	83
70% RCFA	4:43pm	1"	2.9%	143.5	84

Overall, there was not a significant impact of RCA use in paving mixes, even when used at up to 70 percent replacement levels. Figures 4.6 shows some photographs taken while paving the control section and Figures 4.7 and 4.8 show paving photos of the 50% RCFA and 50% RCFA replacements, respectively.

Figure 4.6: Photos showing control mixture being placed, vibrated, and screeded

Figure 4.7: Photos showing 50% RCFA mixture being placed, vibrated, and screeded

Figure 4.8: Photos showing 70% RCFA mixture being placed, vibrated, and screeded

The next morning after paving, pre-cut, partial joints were sawed at each active data acquisition station, as shown in Figure 4.9. This was done to maximize the relevance of the data collected as the pre-cut joints serve as crack initiation points, based on previous work by Won (2022). For each location, three saw cuts, 18" long and 2" deep were cut, with two at the edges and one in the center.

Figure 4.9: Saw cutting of pre-cut joints above vibrating wire gauges at each active monitoring station

The overall construction of the test sections was deemed to be successful. Other than challenges with handling the material, which were overcome, there were no complaints from the contractor regarding the ability to deliver, convey, compact, and finish any of the mixtures, even the 70% RCFA mixture. The primary takeaway is that this trial demonstrated that it is feasible to pave with RCFA contents much higher than the 20 percent current limit for Class P concrete.

4.3. Performance Evaluation and Monitoring of Test Sections

Figure 4.10 shows the compressive strength measured on cylinders cast the day of the field trial. The cylinders were cured on site the first 24 hours, then transported to a fog room for standard curing until the time of testing. Although the strengths measured for the 50% RCFA mixture were higher than the control, and the 70% RCFA mixture showed lower strength than the control, overall, the performance and ultimate strength gain was found to be acceptable.

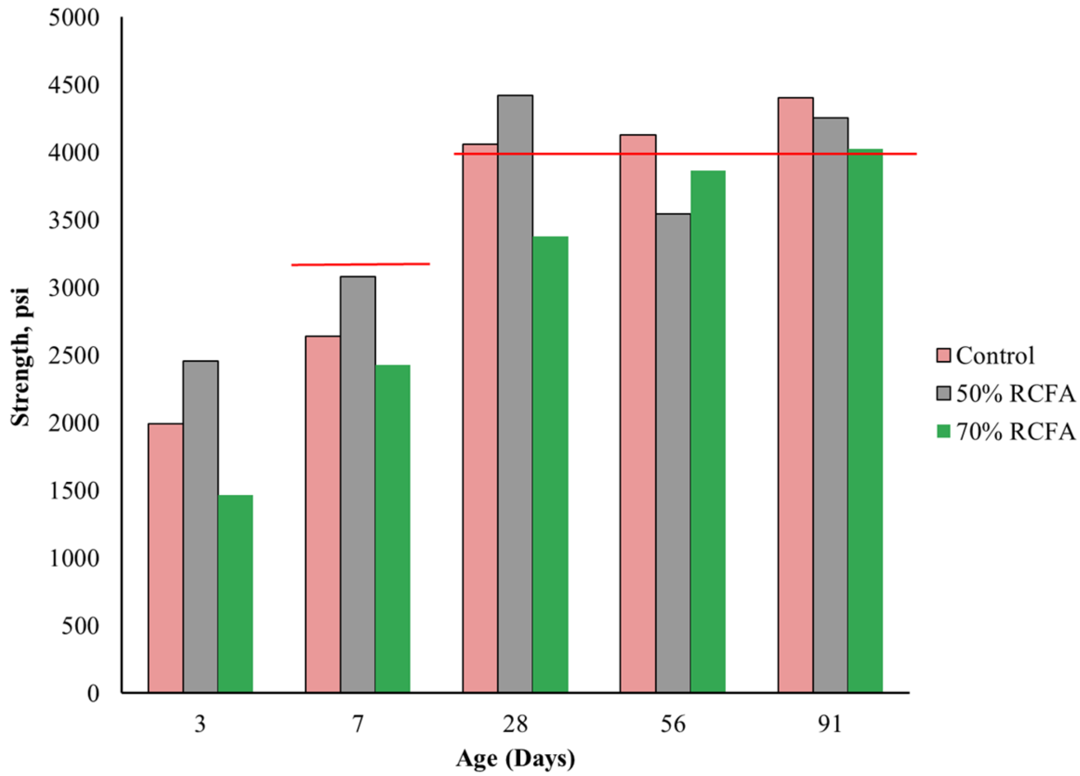

Figure 4.10: Compressive strength of cylinders cast from each test section

Figure 4.11 shows the elastic modulus values measured for field-cast cylinders at 7, 28 and 91 days. As expected with the inclusion of RCFAs, the elastic modulus reduced with increasing RCFA contents, but the overall impact was not very significant (up to about 10 percent reduction for 70 percent RCFA). There is an inherent benefit of lowering the elastic modulus – strains generated by thermal or shrinkage effects will generate proportionally lower stress values. In addition, lower modulus concretes typically exhibit higher creep, which can help to reduce early stresses due to higher relaxation.

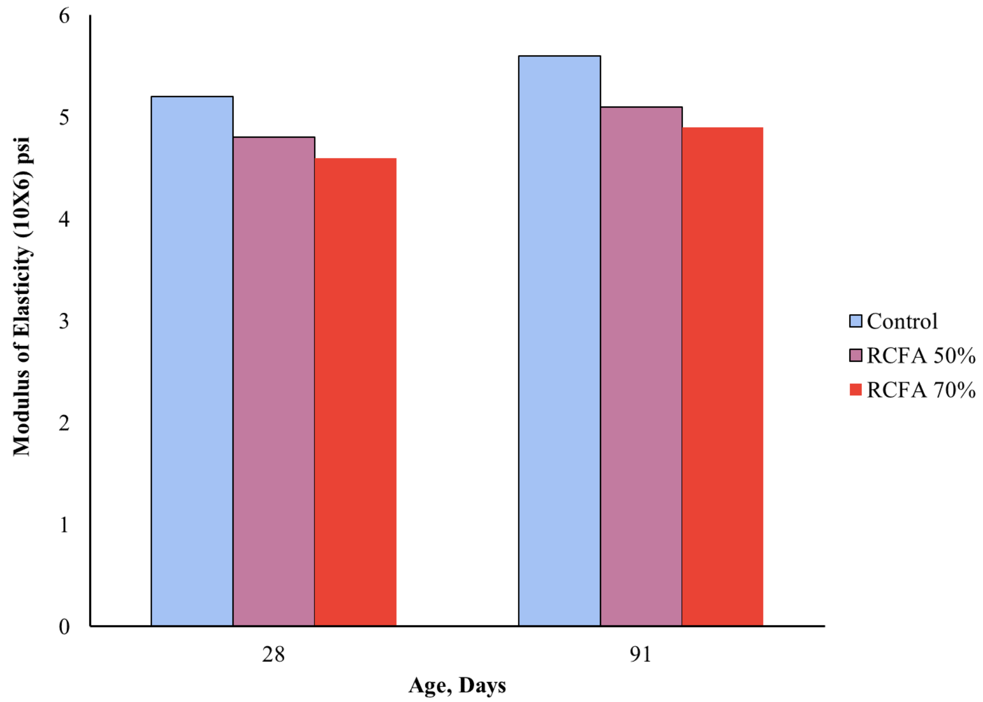

Figure 4.11 Elastic modulus measured on cylinders cast for each test section

Nine days after paving the test section, a monitoring visit was performed. Figure 4.12 shows that the pre-cut joints effectively served as crack initiation points, with three of the four sections exhibiting cracking at the intended locations, and one of the control sections exhibited cracking a few inches from the pre-cut cross section. It should be noted that cracking did eventually occur (after about two months) at the control joint that had exhibited adjacent cracking after nine days.

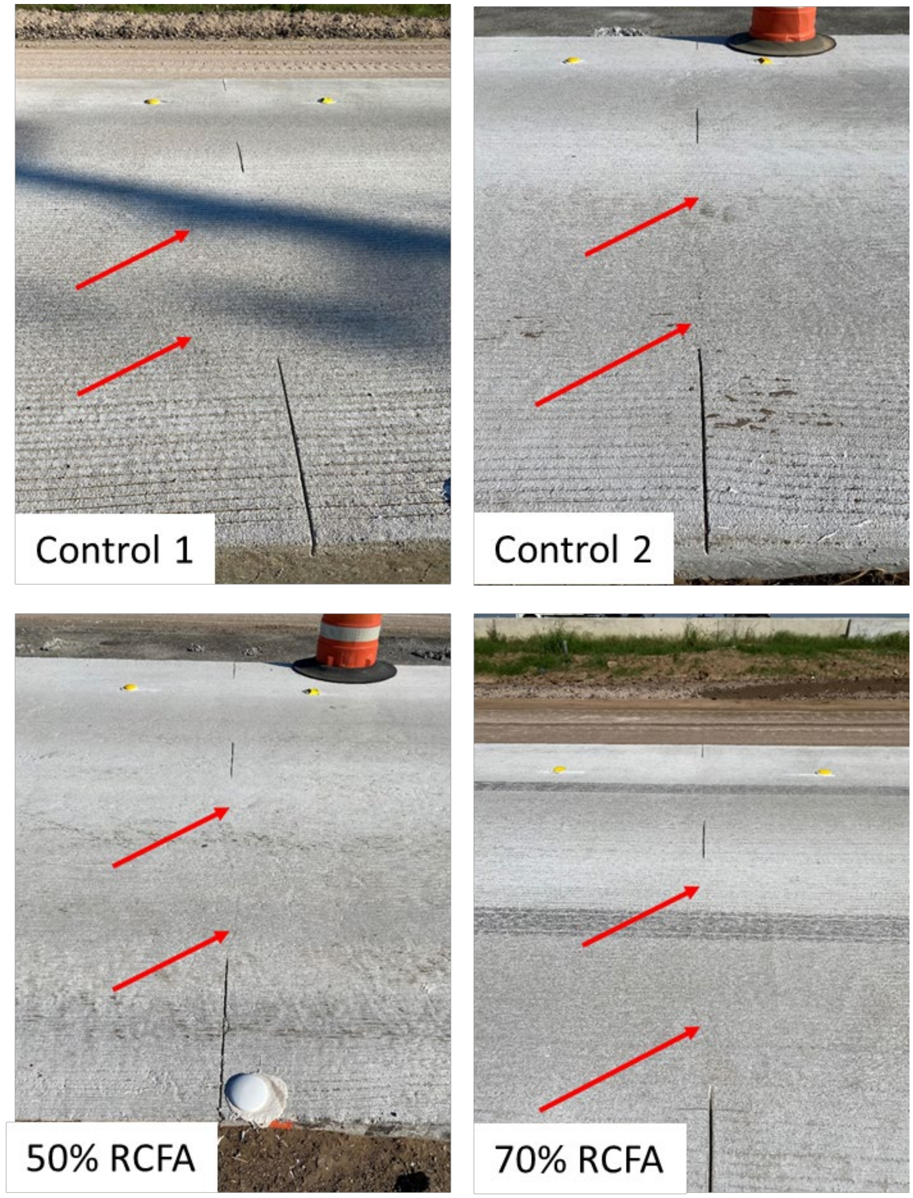

Figure 4.12: Cracking at pre-cut, partial jointed sections nine days after paving

The observed cracking at the pre-cut joints was accompanied by significant changes in strain, mainly caused from a drop in temperature. Figure 4.13 shows typical results (for Control 2) for one of the pre-cut joints, where the measured strain coincided with temperature drop the second night and the observed time to cracking. Cracking was not visible observed 24 hours after paving, but visible cracking was visible after nine days. Based on the vibrating wire gauge, it is evident that cracking occurred at most locations about 36-48 hours after paving.

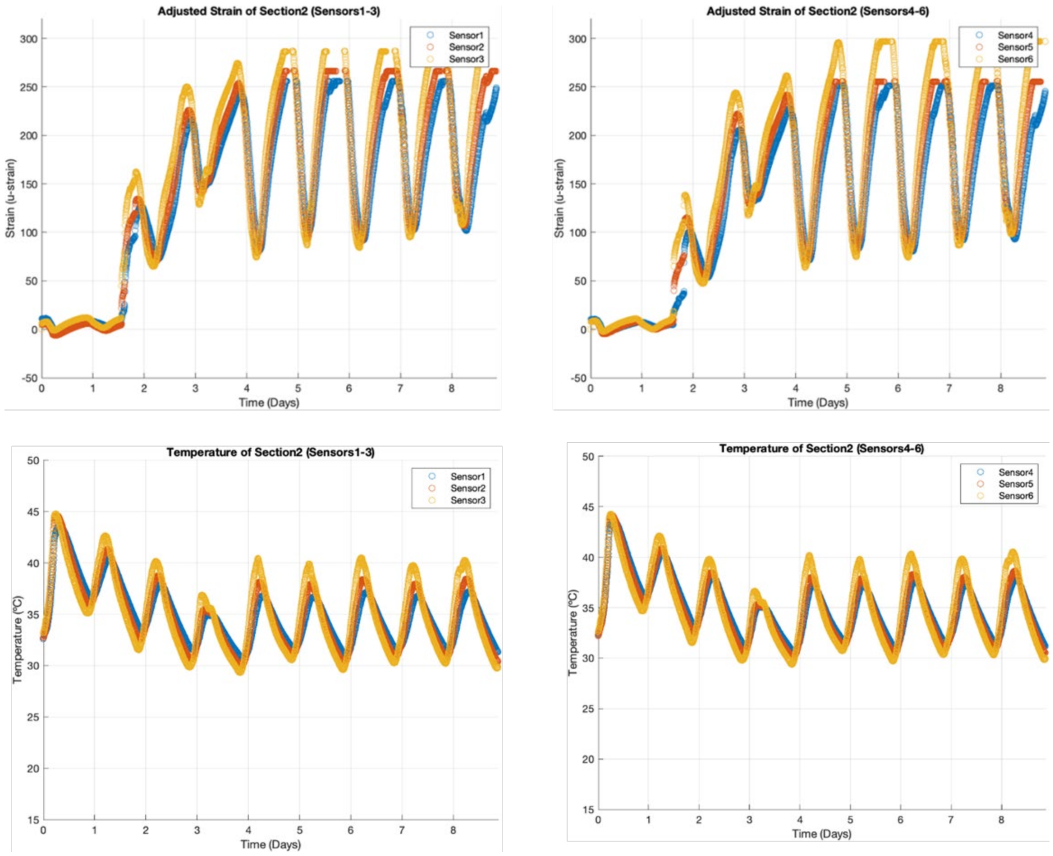

Figure 4.13: Top: Strains (adjusted for temperature) measured by vibrating wire gauges, showing significant shift in strain coinciding with first crack observation at monitoring stations. Below: Temperatures measured by vibrating wire gauges. Significant strains were observed the second night after the pour, coincident with this temperature drop.

A total of four visual surveys were performed for the entire test section, with the primary data being collected were the number and locations of cracks, which is presented in Figure 4.14 as a function of average crack spacing for each test section. There was an observed reduction in average cracking spacing from about 7 ft for the control section to 6 ft for the 50% RCFA section and 5 ft for the 70% RCFA section. Overall, these crack spacings are consistent with typical CRCP performance and further confirms that the inclusion of high replacements levels of RCFA can produce pavements that are constructible and that perform similar to pavements constructed with 100 percent virgin aggregates.

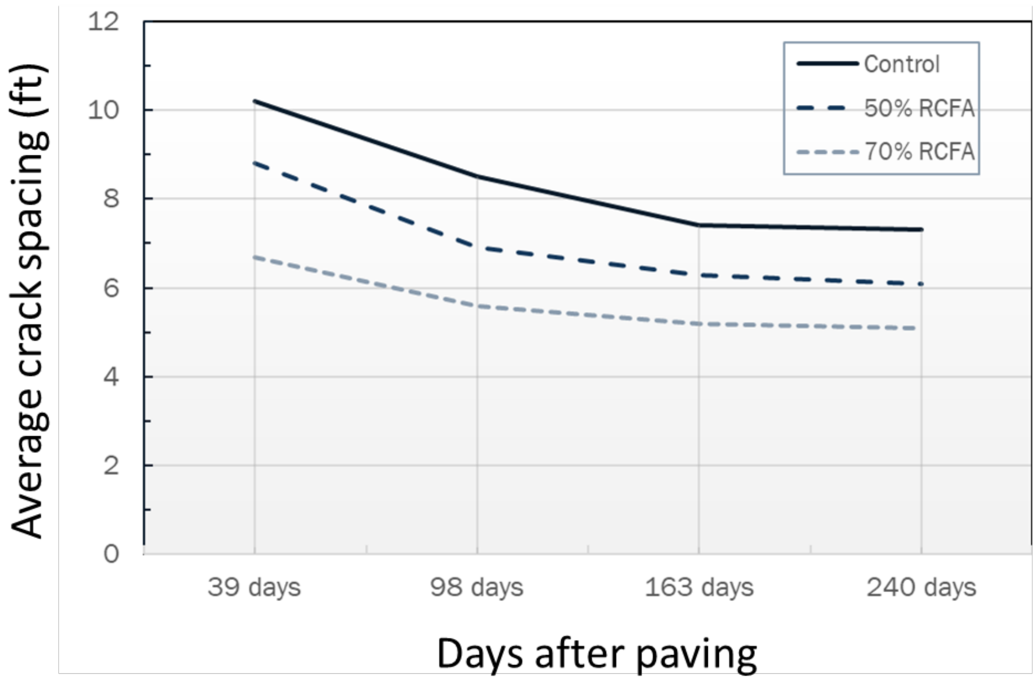

Figure 4.14: Average crack spacings for each of the three test sections

4.4. Summary

The results from this full-scale field trial confirm the positive results obtained in the laboratory testing program of this project. After over eight months of performance monitoring and crack surveying, it can be concluded that RCFA contents as high as 70 percent can be effectively used in CRCP applications, while sill meeting key performance criteria (e.g., workability, constructability, crack spacing, etc.). More work is needed to better document the long-term performance of larger test sections, most suitability inf a full-scale implementation project.

Chapter 5. Conclusions and Recommendations

The overall findings from this study show that it is possible to increase the allowable RCFA content above the current 20 percent limit allowed by TxDOT. This conclusion is based on both a comprehensive laboratory evaluation, which also showed that RCCA can be used at very high replacement levels in Class P concrete, and a full-scale field trial on I-10 in Sealy, TX. Up to 70 percent RCFA was successfully used in the field trial, with performance similar to that of typical Class P concrete using virgin aggregates.

More work is needed to demonstrate the long-term performance of Class P concrete containing high replacement levels of virgin aggregates for RCCA and/or RCFA. Particularly, it is recommended that much larger test sections be constructed to gain more insight into QC/QA issues that might arise in a full production mode. Such efforts are recommended in the form of large-scale implementation projects using RCCA and/or RCFA.

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Appendix A – Value of Research (VoR)

Assumptions for VoR

The Value of Research analysis was performed by considering the following assumptions:

1. It is estimated that 600,000 cubic yards of concrete will be poured by TxDOT every year for 10 years from 2023-2033.
2. It is estimated that concrete paving is responsible for 30 percent of the concrete poured by year on TxDOT projects, and for the purposes of this VoR, RCFA will only be used in Class P paving mixes.
3. It is assumed that recycled concrete fine aggregates (RCFA) are $10/ton cheaper than natural or manufactured sand (FOB). It is estimated that RCFA costs $10/ton, compared to natural or manufactured sand, which costs an estimated $20/ton. The reduced cost of RCFA is based on reduced transportation site, assuming RCFA is produced on-site or nearby, reduced disposal cost, and based on the lower demand for RCFA, compared to natural or manufactured sand.
4. It is assumed that typical Class P concrete contains 1350 lbs/yd3 of fine aggregates or 0.95 tons of fine aggregate per cubic yard of concrete.
5. It is estimated that the average replacement level of virgin sand with RCFA will be 70 percent, which was successfully used in this project and is higher than the current maximum limit of 20 percent.
6. It is assumed that the typical cost of Class P concrete containing virgin aggregates is $120/cubic yard during this 10-year analysis period.

VoR Analysis

The Value of Research analysis calculation, given the above assumptions, is shown below:

Estimated Class P concrete poured over 10-year period (2023-2033)	**Estimated tons of RCFA used over 10-year period (2023-2033)**	**Estimated cost saving by using 70% RCFA in all Class P paving concrete over 10-year period (2023-2033)**
6 million cubic total yards, of which 30 percent is Class P concrete = 1.8 million cubic yards	1.8 million cubic yards of Class P concrete x 0.95 tons RCFA per yard = 1,710,000 tons	1,710,000 tons RCFA x $10/ton cost saving per ton = **$17.1 million**

Summary of Estimated Economic Benefits

Based on the above VoR analysis, it is estimated that the economic benefits derived from this project's findings and recommendations are approximately $17.1 million over a 10-year period (2013-2023). This estimate could go much higher if RCFA were used in other Classes of concrete besides Class P. In addition, increasing the percent replacement levels to 100 percent would further increase the economic benefits, while also removing the need for a separate stockpile of virgin sand.